



**Feasibility of optimizing log sorting and
lumber manufacturing processes by using
X-ray scanning to characterize check severity
in mountain pine beetle-affected logs**

Jan Brdicko

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FPIInnovations–Forintek Division
2665 East Mall, Vancouver, BC V6T 1W5

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Abstract

Checks that develop in trees killed by the mountain pine beetle cause lumber value losses from 17% to 40%. Studies have shown that sawing patterns can be adjusted to minimize the effects of the checks and that lumber recovery and value losses can be reduced significantly if check locations and depths were accurately known. This research has shown that X-ray scanning systems with six views can detect and characterize larger open checks with an accuracy that depends on the check width and orientation relative to the direction of X-rays. A series of sawmill breakdown simulations of checked logs was used to determine the potential increase in value recovery and return on investment (ROI) from using X-ray scanners for optimization of log sorting and breakdown of MPB-killed trees. These simulations showed that a six-view scanner has the potential to correctly identify 50% to 60% of the checks and, when this information is used to optimize manufacturing of lumber, can on average increase the value recovery by approximately 50% of the theoretical maximum that a perfect X-ray scanner would achieve. A sensitivity analysis determined that the ROI of a six-view X-ray scanner is insufficient when the log supply is lightly checked. However, for log supplies mainly comprised of medium- to severely checked logs, the ROI can be as high as 27%.

Keywords: lodgepole pine, lumber recovery, saw logs, cracks, checks, sawing patterns, check depth, check width, log sorting, log breakdown, X-ray log scanner, multi-view X-ray scanner, image processing, radiograph, ROI, OPTITEK® simulation

Résumé

Les gerçures qui se développent dans les arbres tués par le dendroctone du pin ponderosa entraînent des pertes de valeur du bois de l'ordre de 17 % à 40 %. Les études ont démontré que les plans de débit peuvent être ajustés pour minimiser les effets des gerçures et que la régénération du bois ainsi que les pertes de valeur peuvent être réduites de façon considérable si la zone et la profondeur des gerçures sont connues de façon précise. Cette recherche a démontré que les systèmes d'inspection par rayons X de six vues peuvent détecter et définir de grandes gerçures ouvertes avec une précision proportionnée à la largeur et à l'orientation de la gerçure par rapport à la direction des rayons X. Une succession de simulations de débitage des billes atteintes de gerçures ont été utilisées dans une usine de bois de sciage pour déterminer l'augmentation possible de la récupération de la valeur et le rendement du capital investi (RCI) obtenu par l'utilisation d'appareils de détection à rayons X pour l'optimisation du triage des billes et du débitage des arbres tués par le DPP. Ces simulations ont démontré qu'un balayeur à six vues a la possibilité d'identifier de façon précise de 50 % à 60 % des gerçures et, lorsque cette information est utilisée pour la fabrication du bois de sciage, peut, en moyenne, augmenter la récupération de la valeur d'environ 50 % du maximum théorique qu'un appareil de détection à rayons X parfait pourrait réaliser. Une analyse de sensibilité a déterminé que le RCI d'un balayeur à six vues est insuffisant lorsque l'approvisionnement en billes n'est que légèrement atteint de gerçures. Toutefois, pour ce qui est des approvisionnements de billes comprenant essentiellement des billes atteintes de gerçures de gravité moyenne à sévère, le RCI peut être aussi élevé que 27 %.

Mots clés : pin tordu latifolié, récupération du bois de sciage, billes de sciage, craquelures, gerçures, plans de débit, profondeur de la gerçure, largeur de la gerçure, triage des billes, débitage des billes, dispositif de balayage des billes par rayons X, appareils de détection à rayons X multivues, traitement des images, radiogramme, RCI, simulation OPTITEK®

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1 Introduction

The forest products industry in British Columbia is currently suffering from a number of issues that threaten the viability of many sawmills. One of these issues is the massive mountain pine beetle (MPB) attack that has killed millions of hectares of lodgepole pine stands in the British Columbia Interior. Consequently, the fibre supplies of sawmills in the Interior contain very large quantities of stained and check-damaged logs.

The checks that develop in beetle-affected trees and logs lead to significant losses in lumber value. Studies have shown that if the location and depth of checks are accurately known, sawing patterns can be adjusted to maximize lumber recovery and minimize losses of value.

Research done prior to this project and field tests of a commercial European X-ray log scanner have shown that under certain conditions the scanner could detect checks such as those that occur in beetle-affected saw logs. And, most promisingly, the scanner could also measure the check depth. This preliminary work also showed that there were considerable gaps in basic knowledge about how X-ray scanners could be used for optimizing lumber recovery and value from beetle-affected logs. Further work was required to determine which checks can be detected, how accurately they can be measured, and the minimum system requirements for optimizing log sorting and breakdown.

Consequently, this project examined the feasibility of using X-ray scanning to detect the location and size of the checks and also examined the fiscal viability of incorporating a system in a typical BC interior sawmill.

1.1 About checks

1.1.1 Characterization of checks

Checks in logs, whether measured manually or scanned by X-ray scanners, need to be characterized (or modeled) in a format suitable for the intended use. The format required in this study was for use in OPTITEK®, Forintek's sawmill simulation software for log sorting and breakdown optimization (see Appendix A), used for processing log images made by an X-ray scanner. The format for characterizing checks in logs is shown in Figure 1.

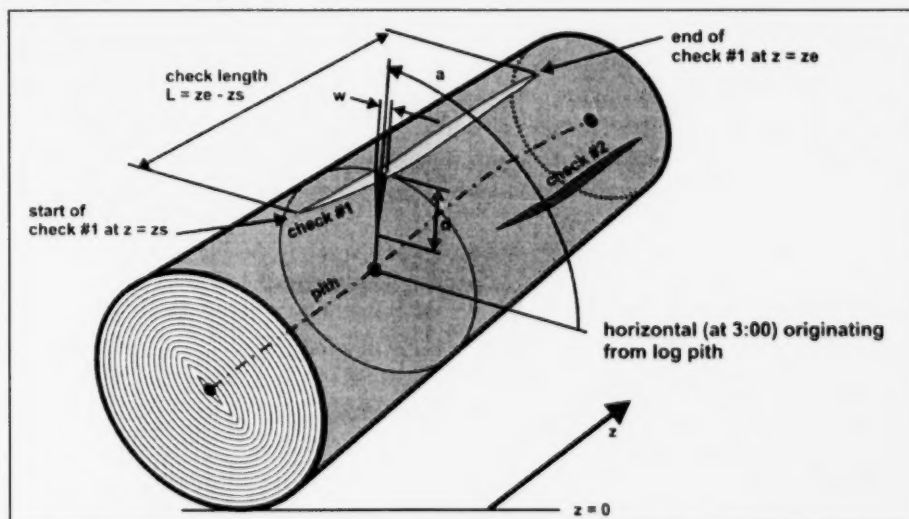


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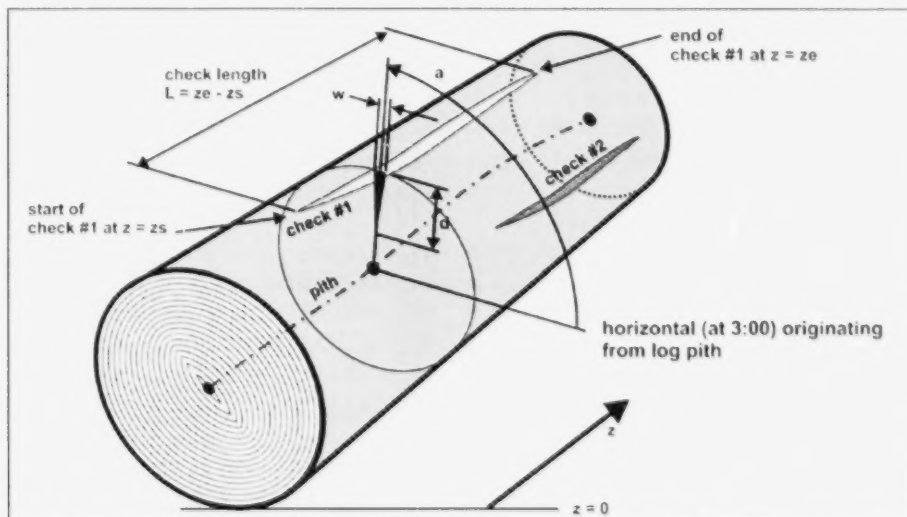


Figure 1. Characterization of checks.

A check is assumed to be triangular in cross-section (with straight sides) and to be oriented towards the log pith. In cross-section, at distance z (Figure 1), each check is identified by:

- a unique number (1,2,...);
- the counter-clockwise angle α from horizontal (at 3 o'clock), or similar reference;
- width w at log surface; and
- depth d from the log surface.

The check characterization in this format may be adequate when the check data are provided at small increments along the log length. But if this is not possible, some additional heuristic rules are needed to complement the check data.

For example, a check of interest is one that is sufficiently large i.e., where depth d is >1.0 inch and length L is >10.0 inches (as it is not likely that shorter checks would be deep). If a check spans a knot cluster (where it cannot be detected by X-ray scanning—as discussed later), the parts of the check on each side of the knot cluster need to be “connected” into one check of total length $L = L_1 + L_2 + L_3$, as shown in Figure 2.

Most checks are continuous, but a check may “jump” laterally up to several inches, particularly if it crosses a knot. Again, these checks need to be connected. A check usually follows the grain direction. Because most logs processed in a sawmill have grain twist $<5\%$, checks are usually nearly parallel to the pith.

The above check characterization format and heuristic rules use the least number of parameters to describe checks in logs, while approximating with an acceptable degree of accuracy most natural checks occurring in beetle-affected logs. The same format would also be suitable for use by commercial, real-time software used in sawmills. It has to be appreciated that when applying this check characterization format and the heuristic rules to checks with greatly different characteristics, such checks may go undetected and/or be inaccurately represented by the log-sorting and breakdown-optimization software.

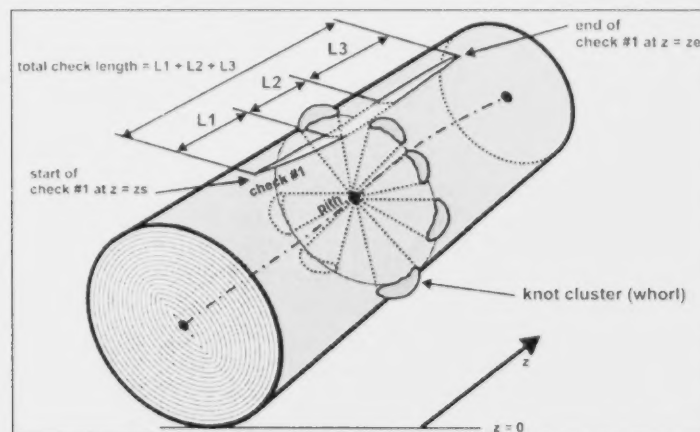


Figure 2. Check spanning a knot cluster

1.1.2 Effects of checks on lumber recovery

Numerous studies (Barrett 2007; Orbay and Goudie 2006a) have shown that checking is the main reason that lumber recovery and value from beetle-affected saw logs are reduced. The losses in value recovery can be in the range of 17 to 40%, or higher, depending on the severity of checking. Figures 3 and 4 illustrate how checks reduce lumber recovery.

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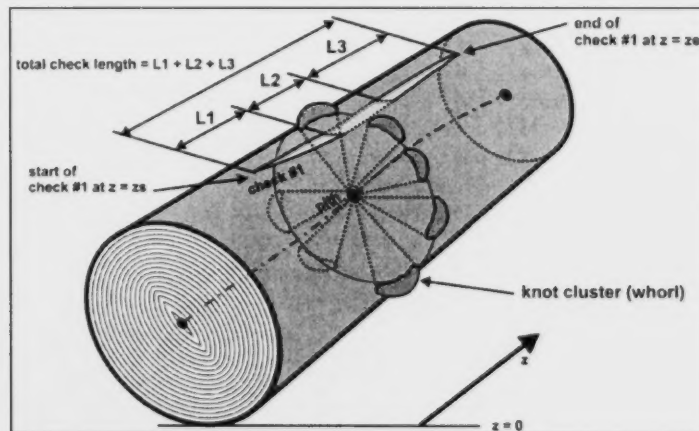


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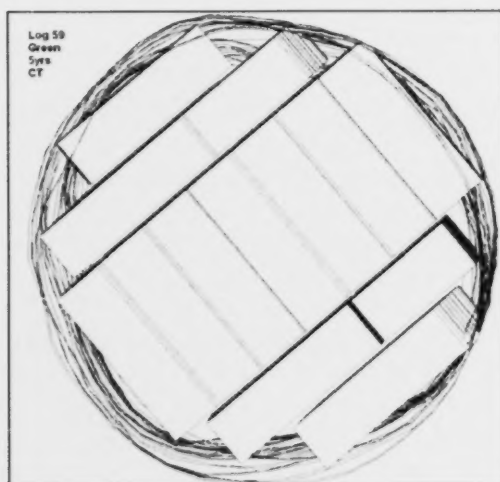
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Figure 3 shows an optimal sawing pattern for a healthy log with no checks. Figure 4 shows a beetle-affected log with the same shape but which also contains checks. The sawing patterns are identical because the current sawmill does not utilize technologies to detect checks; the sawing pattern is therefore based only on the log shape. However, because the second log contains checks, some of the boards in the sawing pattern are degraded, shortened, or lost altogether. This results in loss of volume recovery and an even greater loss of value recovery.

Studies have also shown that if the location and depth of the checks are accurately known the effects of checks could be minimized because a different sawing pattern could be determined (Orbay and Goudie 2006b). For the shape of log shown in Figures 3 and 4 such a pattern is shown in Figure 5.

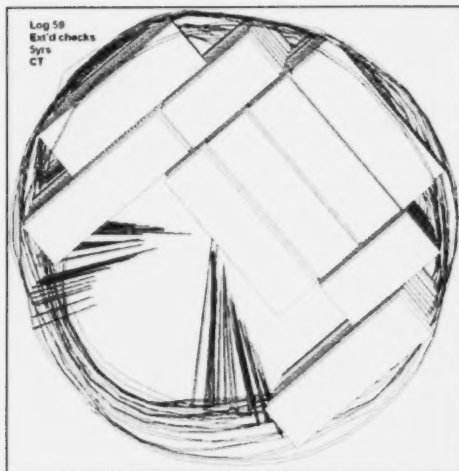
The sawing pattern shown in Figure 5 could be realized if all mill machine centers would utilize technologies able to perfectly detect checks, or have the check information provided in some way, and could use this knowledge in breakdown optimization. This optimum sawing pattern usually has a different log rotation angle and other settings of machine centers and generates higher recovery than the current mill (Figure 4), but lower recovery than would be realized from the healthy log (Figure 3). This solution has the theoretical maximum lumber value recovery that could be extracted from the checked log.



**Green lumber products:
Log 59 5yrsHealthy CT**

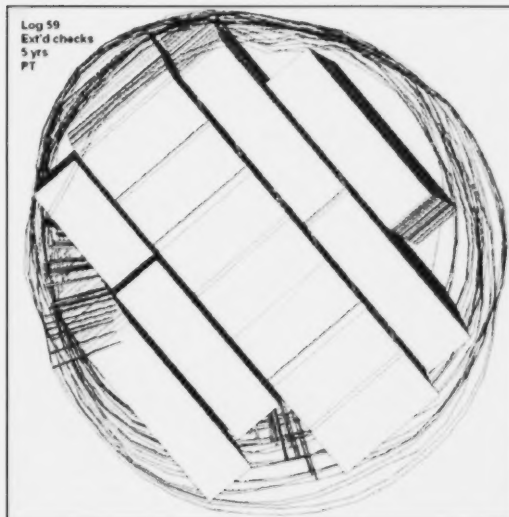
Thickness × width × length (cm)	OPTITEK® grade	Lumber pieces (no.)
1.654 × 5.77 × 98	4	1
1.654 × 3.73 × 196	2	1
1.654 × 5.77 × 196	4	2
1.654 × 5.77 × 122.5	5	2
1.654 × 5.77 × 196	1	5
1.654 × 5.77 × 196	5	1
1.654 × 3.73 × 98	4	1
Total pieces(no.)		13
Total lumber volume (fbm)		172
Volume recovery (fbm/m ³)		366

Figure 3. Healthy log: optimal sawing pattern and green lumber products obtained. Optitek grades are defined in Appendix F.



Green lumber products: Log 59 5yrsAATSCT		
Thickness × width × length (cm)	OPTITEK® grade	Lumber pieces (no.)
1.654 × 5.77 × 98	4	1
1.654 × 3.73 × 196	2	1
1.654 × 5.77 × 122.5	5	2
1.654 × 5.77 × 196	1	3
1.654 × 5.77 × 196	4	1
1.654 × 3.73 × 98	4	1
Total pieces (no.)		9
Total lumber volume (fbm)		108
Volume recovery (fbm/m ³)		230

Figure 4. Log with checks, no check-detection technology (location of checks unknown): optimal sawing pattern and green lumber products obtained. Optitek grades are defined in Appendix F.



Green lumber products: Log 59 5yrsAATSPT		
Thickness × width × length (cm)	OPTITEK® grade	Lumber pieces (no.)
1.654 × 5.77 × 196	4	3
1.654 × 5.77 × 196	5	1
1.654 × 3.73 × 171.5	5	1
1.654 × 3.73 × 196	4	3
1.654 × 3.73 × 147	5	1
1.654 × 3.73 × 196	1	2
1.654 × 3.73 × 196	2	1
1.654 × 5.77 × 196	2	1
Total pieces (no.)		13
Total lumber volume (fbm)		161
Volume recovery (fbm/m ³)		343

Figure 5. Log with checks determined by check-detection technology (location of checks known): optimal sawing pattern and green lumber products obtained. Optitek grades are defined in Appendix F.

1.1.3 Detecting checks

Virtually all sawmills now optimize log breakdown by using laser scanners to measure the external shape of the log. However, these systems cannot detect checks. Although several manufacturers have developed vision-based systems that detect cracks and checks, these systems work only on debarked logs (which is too late for sorting and merchandizing applications). Also, their check-detecting ability is not reliable and they cannot measure the check depth, which is the most critical parameter for an optimal sawing pattern.

A CT (computed tomography) X-ray scanner would be ideal for scanning logs it can produce images of log cross-sections that show checks, knots, and other features in remarkable detail. The images are created by processing hundreds of X-ray pictures that are taken of the log as it is rotated during scanning, or as the X-ray assembly rotates around the stationary log. An example of such an image appears in Figure 6.

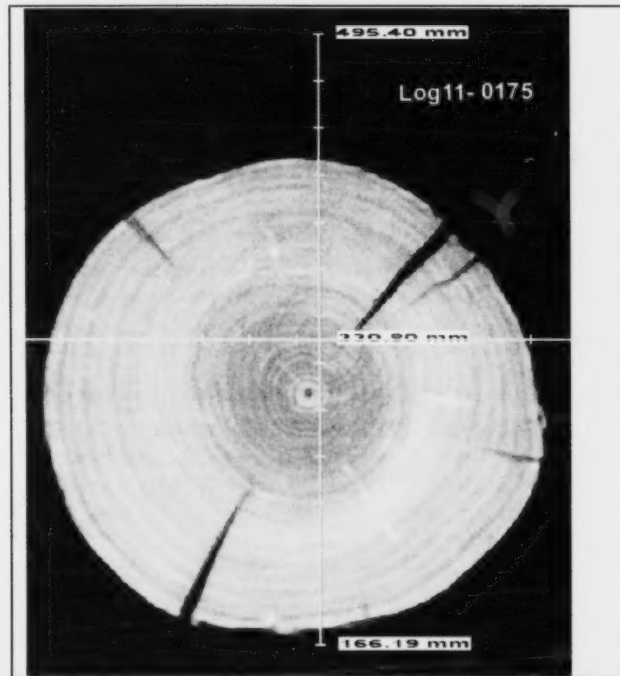


Figure 6. Cross-sectional image of a log containing checks, taken by a CT X-ray scanner.

Unfortunately, the very high cost and the design and performance limitations of current CT X-ray scanners preclude their use in mill operations now and in the foreseeable future.

To overcome these limitations, at least in part, scanner manufacturers have developed X-ray scanners that provide up to six views. The small number of views makes it impossible to construct images of log cross-sections showing features such as checks. However the X-ray data from the different views can be processed by special algorithms to estimate the approximate size and location of features such as knots, checks, rocks, nails, etc., by using some additional knowledge about these features, such as shape and density.

These images of log cross-sections that can be provided by these multi-view scanners are fundamentally different from those generated by CT X-ray scanners. The images consist of the log cross-section shape usually provided by the laser scanner (or an approximate shape if a laser scanner is not used) with the models of the features (such as checks) placed within the cross-section shape. The accuracy of these images depends on the number of views; the characteristics, size, and location of the specific features; and the differences between the actual features and their models, etc.

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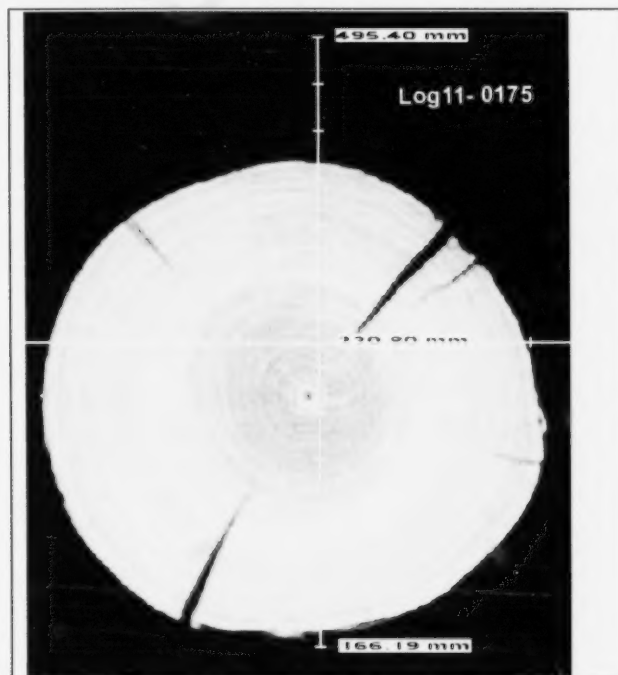


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1.2 Potential of X-ray scanners to increase lumber recovery

Determining an ideal sawing pattern requires accurate information about check characteristics.

Based on the preliminary research, it was expected that a multi-view X-ray scanner would detect most of the larger checks and characterize them with accuracy sufficient to improve recovery.

A multi-view X-ray scanner would not be expected to “see” some checks at all, and of those it could “see” it could not measure their depth and width with perfect accuracy. Consequently, the resulting sawing pattern would be different than the ideal sawing pattern shown in Figure 5.

If a multi-view X-ray scanner that cannot provide highly accurate data were used in a sawmill, some of the boards in the sawing pattern could be downgraded or lost altogether due to the checks, meaning that the value recovery with the less accurate scanning system would be always lower than, or at best equal to, the value recovery obtained from using the most sophisticated X-ray scanner.

Given that a commercial multi-view X-ray scanner was expected to be less than perfect, an investigation was required to assess the use of these X-ray scanners for optimizing log sorting and breakdown. The measure of how well an X-ray scanner detects and deals with checks, termed “check-detection capability,” is defined as 0% for a sawmill without X-ray scanning, and 100% for the perfect system.

The research project included the following tasks:

1. Survey the literature and technology of digital X-ray scanners and investigate approaches used to extract quantitative information about the features of interest (such as checks) (Brdicko 2008a, b, c, d).
2. Development and use of an image processing application (IPA) to facilitate processing of radiographs of log cross-sections to detect checks and estimate their location, width and depth, and simulate a digital X-ray scanner.
3. Use the FPInnovations–Forintek/UNBC CT X-ray scanning system to collect radiographs of:
 - fabricated wooden discs with artificially created checks,
 - “cookies” cut from beetle-affected stems, and
 - six beetle-affected logs that include checks covering the full range of widths and depths (Brdicko 2008a, b, c, d).
4. Analyze the experiment’s results to determine the factors that limit check detection, and to determine the accuracy with which check location, width, and depth can be estimated.

Items 1 and 2 and a part of item 3 were completed in the 2007/08 portion of this project. The research completed in the 2008/09 period is described in the sections below.

The objectives of this project were:

- Investigate the ability of X-ray based scanning systems to detect and characterize checks in beetle-affected logs.
- Determine the minimum technical requirements of a practical on-line scanner system suitable for optimizing log sorting and sawing breakdown in a sawmill.
- Determine the potential increase in lumber value recovery associated with implementing such a system, and estimate the return on investment.

2 Research Components

2.1 Detecting checks in radiographs produced by a one-view X-ray scanner

This section discusses the ability of a single X-ray source—a one-view X-ray scanner—to detect and measure checks in logs.

2.1.1 Check visibility ranges

Figure 7 shows how the near visibility angle n (also referred to as “range”) and the far visibility angle f , for a check of width w , are defined here.

A check can be detected (i.e., is “visible”) within these angles, which are measured relative to the coordinate system of the particular view at angle α relative to the machine coordinates. The log cross-section is assumed to be positioned such that the pith is at the origin of the machine coordinates. With commercial X-ray scanning systems, the log cross-section may be positioned with the pith at offsets several inches from the origin of the machine coordinates, depending on the log diameter and sweep. The analyses and tests undertaken during this study have shown that these offsets have negligible effects on the accuracy of check visibility ranges when the calculations are based on the assumption that the pith is located at the origin of the machine coordinates.

Measurements of visibility angles in fabricated wooden discs and cookies cut from beetle-affected logs were summarized in tables such as Table 1.

In Table 1, the values for the near visibility angle n are identified as “Near peak range (deg)” and values for the far visibility angle f are identified as “Far peak range (deg)”. Figure 8, which is based on Table 1, shows the plot that relates the widths of the checks and the visibility angles (referred to as “ranges”), including the lines fitting the data. A check is defined as “visible” if the height of the peak (caused by the check) in the radiograph is $>4\%$ of the radiograph data range.

Similar tables and plots were produced for 6-inch and 18-inch MPB cookies and these are included in Appendix B. The slopes of the lines fitting the data in the three plots were used to relate diameters of the cookies and the visibility angles, as shown in Figure 9 which also includes the second-order polynomial fitting the data.

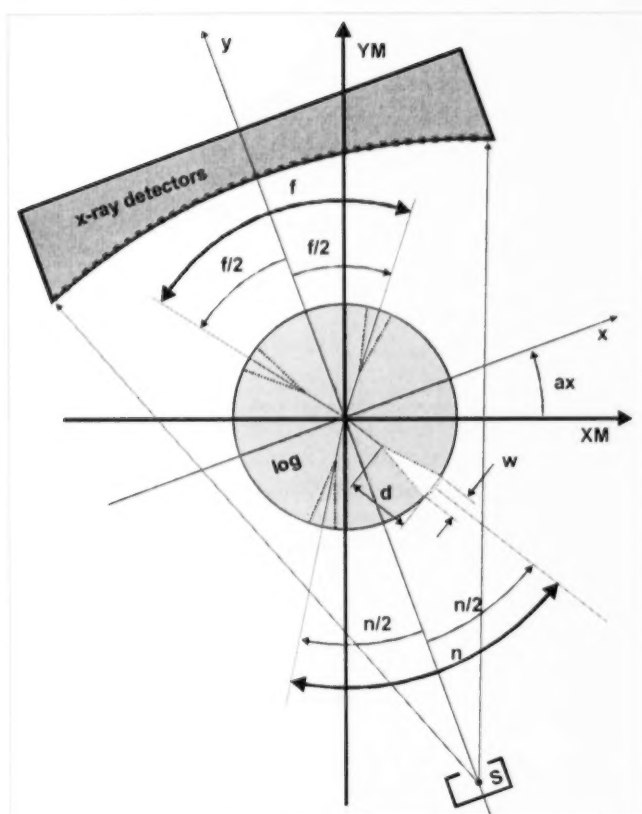


Figure 7. Check visibility ranges of one-view system.

Table 1. Summary of results of X-ray scanning of 12" MPB cookies.

offset X	check width		check depth			peak visibility data												total range	% of 360
[in]	[in]	% radius	[in]	% radius	% diameter	near peak					far peak								
						peak height	peak angle [deg]	start angle [deg]	end angle [deg]	range [deg]	peak height	peak angle [deg]	start angle [deg]	end angle [deg]	range [deg]				
0	0.08	1	5.6	86	43	62	103	96	105	9	64	283	274	286	12	21	6		
0	0.35	5	4.6	71	36	81	101	84	125	41	79	282	260	310	50	91	25		
0	0.37	6	2.3	36	18	73	100	90	126	36	72	279	265	325	60	96	27		
0	0.38	6	6.1	94	47	101	101	84	124	40	97	283	263	310	47	87	24		
0	0.41	6	2.0	31	15	74	102	86	130	44	74	281	255	320	65	109	30		
0	0.45	7	4.4	69	34	86	101	83	125	42	83	282	255	310	55	97	27		
0	0.63	10	6.1	94	47	103	100	80	130	50	100	281	250	310	60	110	31		
0	0.64	10	2.0	31	16	61	100	82	131	62	60	283	248	328	80	142	39		
0	0.75	12	4.1	63	32	84	100	76	134	58	85	281	245	310	65	123	34		
5	0.08	1	5.6	86	43	29	96	81	98	17	24	260	252	271	19	36	10		
5	0.35	5	4.6	71	36	76	107	91	125	34	76	284	260	315	55	89	25		
5	0.37	6	2.3	36	18	71	105	97	131	34	68	283	271	310	39	73	20		
5	0.38	6	6.1	94	47	94	108	91	124	33	93	286	255	315	60	93	26		
5	0.41	6	2.0	31	15	40	105	92	131	39	70	285	260	320	60	99	28		
5	0.45	7	4.4	69	34	81	107	90	128	38	81	284	255	320	65	103	29		
5	0.63	10	6.1	94	47	98	105	85	125	40	98	285	250	320	70	110	31		
5	0.64	10	2.0	31	16	69	105	88	132	44	67	283	260	338	78	122	34		
5	0.75	12	4.1	63	32	82	105	84	134	50	83	283	245	323	78	128	36		

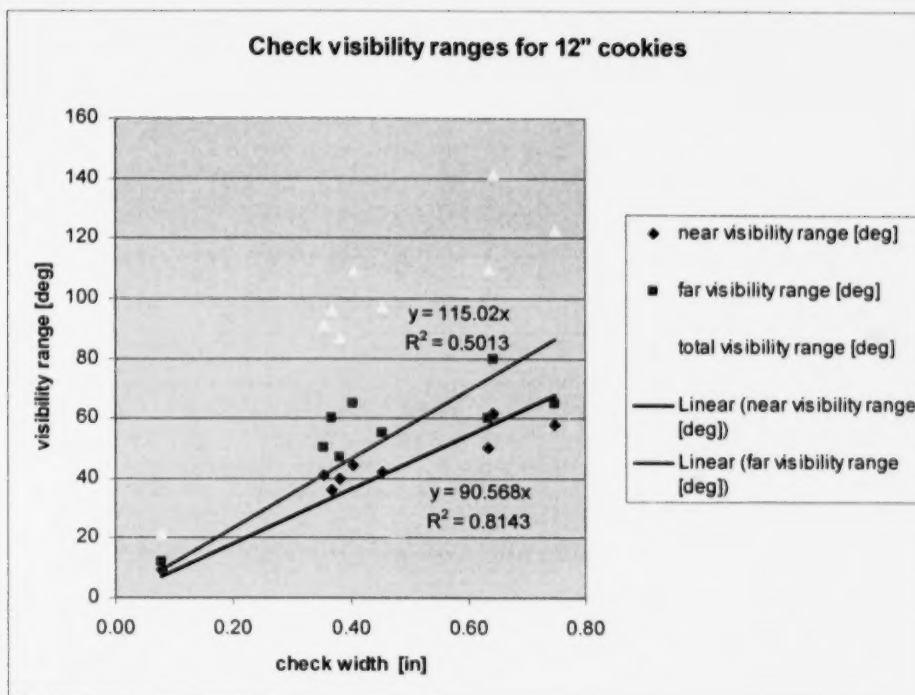


Figure 8. Check visibility ranges for 12-inch cookies obtained from beetle-affected logs.

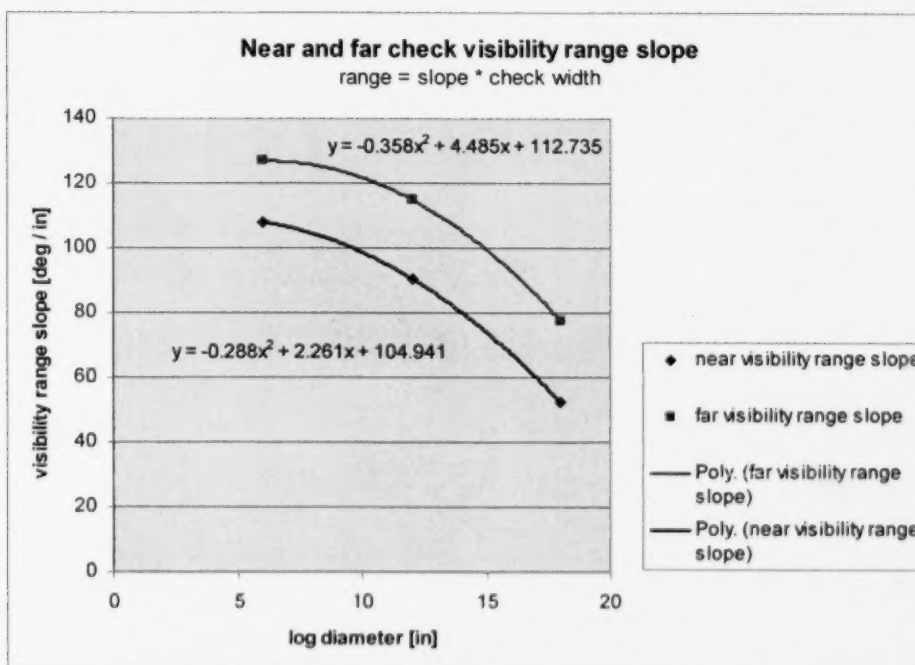
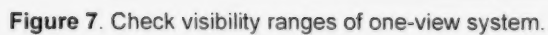


Figure 9. Check visibility range slopes of MPB cookies of different diameters.



offset X	check width		check depth			peak visibility data											
[in]	[in]	% radius	[in]	% radius	% diameter	near peak					far peak					total range	% of 360
						peak height	peak angle [deg]	start angle [deg]	end angle [deg]	range [deg]	peak height	peak angle [deg]	start angle [deg]	end angle [deg]	range [deg]		
0	0.08	1	5.6	86	43	62	103	96	105	9	64	283	274	286	12	21	6
0	0.35	5	4.6	71	36	81	101	84	125	41	79	282	260	310	50	91	25
0	0.37	6	2.3	36	18	73	100	90	126	36	72	279	265	325	60	96	27
0	0.38	6	6.1	94	47	101	101	84	124	40	97	283	263	310	47	87	24
0	0.41	6	2.0	31	15	74	102	86	130	44	74	281	255	320	65	109	30
0	0.45	7	4.4	69	34	86	101	83	125	42	83	282	255	310	55	97	27
0	0.63	10	6.1	94	47	103	100	80	130	50	100	281	250	310	60	110	31
0	0.64	10	2.0	31	16	61	100	82	131	62	60	283	248	328	80	142	39
0	0.75	12	4.1	63	32	84	100	76	134	58	85	281	245	310	65	123	34
5	0.08	1	5.6	86	43	29	96	81	98	17	24	260	252	271	19	36	10
5	0.35	5	4.6	71	36	76	107	91	125	34	76	284	260	315	55	89	25
5	0.37	6	2.3	36	18	71	105	97	131	34	68	283	271	310	39	73	20
5	0.38	6	6.1	94	47	94	108	91	124	33	93	286	255	315	60	93	26
5	0.41	6	2.0	31	15	40	105	92	131	39	70	285	260	320	60	99	28
5	0.45	7	4.4	69	34	81	107	90	128	38	81	284	255	320	65	103	29
5	0.63	10	6.1	94	47	98	105	85	125	40	98	285	250	320	70	110	31
5	0.64	10	2.0	31	16	69	105	88	132	44	67	283	260	338	78	122	34
5	0.75	12	4.1	63	32	82	105	84	134	50	83	283	245	323	78	128	36

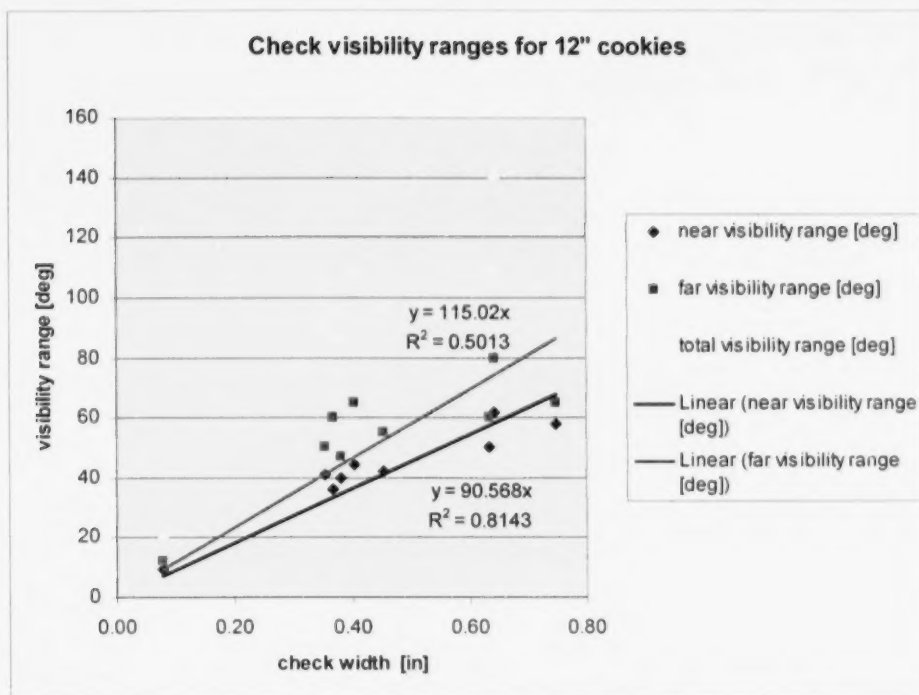


Figure 8. Check visibility ranges for 12-inch cookies obtained from beetle-affected logs.

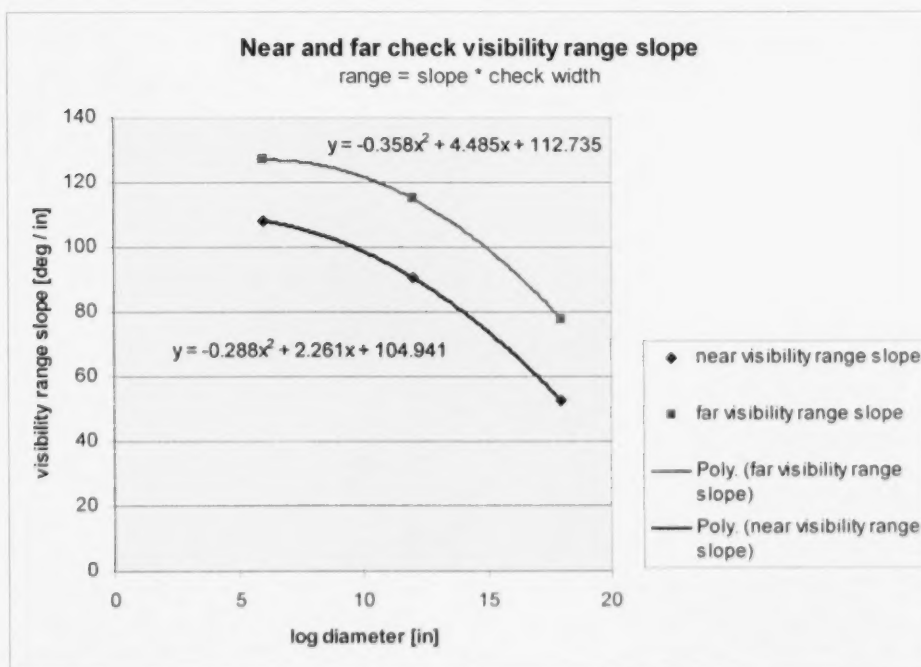


Figure 9. Check visibility range slopes of MPB cookies of different diameters.

Referring to Figure 9, for a log cross-section with an average diameter D , and a check of width w , the near and far visibility angular ranges n and f of the check are calculated using the equations below:

$$\begin{aligned} n &= n_s w = (-0.288D^2 + 2.261D + 104.941)w \\ f &= f_s w = (-0.358D^2 + 4.485D + 112.735)w \end{aligned} \quad [1]$$

where n_s is the near visibility range slope, and f_s is the far visibility range slope.

Equation 1 can be used to determine whether a check in a particular cross-section of a log is visible with an X-ray scanner.

2.1.2 Check position, width, and depth

Experimental measurements of angular check position and width in fabricated wooden discs with artificial checks and cookies have been discussed in Brdicko 2008d. Measurements of angular check position, width, and depth were obtained with the aid of an image processing application developed for the data processing and X-ray scanner simulation. The measurements were made by software modules of the image processing application utilizing algorithms having accuracy such as would be expected to be developed by a commercial X-ray scanner provider.

Figure 10 shows an example of the image processing application's screen, including the summary of measurements that was generated after the entire set of 1000 radiographs of a 10-inch diameter medium density fibreboard (MDF) disc was processed. The radiographs included X-ray images of the disc taken at viewing angles from 0°– 360° in 1000 angular increments. The software measured angular check position, width, and depth at the viewing angles where the check was visible. Depending on the check width, the number of angular increments ranged from a few for narrow checks to 50 or more for wide checks. The image processing application summarized the measurements by an average value and a standard deviation.

This disc had one large machined check measuring 0.63 inches wide and 3.18 inches deep. Check position was measured with an error of -0.06° and a standard deviation of 0.79° . Check width was measured with error of -0.20 inches and a standard deviation of 0.10 inches. Measurements of angular check position and width in numerous other cookies had similar high degree of accuracy, which we believe is more than adequate for the purposes of log sorting and breakdown optimization. Further collection of these measurements was deemed unnecessary. The focus shifted to issues related to measuring check depth, which is a much more critical check characteristic than the accuracy of check position and width.

Measurements of check depth made by the image processing application's software, utilizing the initial algorithms presented in previous reports (Brdicko 2008a, b, c, d), were reasonably accurate for MDF discs and for some nearly perfectly homogenous beetle-affected cookies, as measured by an average error; but, the standard deviation was too high. Figure 10 shows that the check depth of a fabricated disc was measured with an error of -0.20 inches and a standard deviation of 0.75 inches using the first algorithm, and with an error of -0.12 inches and a standard deviation of 0.48 inches using the second algorithm. The accuracy of check depth measurements in other, more typical beetle-affected cookies was considerably worse, to the point where an X-ray scanner using algorithms such as the initial algorithms developed in this project would not deliver sufficient accuracy to facilitate log sorting and optimization.

Subsequent analysis of the initial algorithms identified that the main reason for the inaccuracy of check depth estimate was the very high sensitivity to the unavoidable small variation (i.e., "noise") in the X-ray scanner's raw data, such as shown in Figure 11. This figure shows a part of the raw data, including a peak corresponding to the check in the log cross-section shown in Figure 12.

In the initial algorithms, the peak in the raw data of a log cross-section is quantified by the largest peak height h and the width of the right part of the peak w_r . The peak height is measured relative to the interpolating curve, which is the best "guess" of what the raw data would be if there was no check in the log cross-section. The estimation of the check depth involves the ratio h/w_r . This ratio is similar to the ratio of check depth and check width, which is typically 10 or more; thus even a 5% error in the measurement of h and w_r may cause a 50% error in the depth estimate.

Therefore, further research was undertaken to develop a more accurate algorithm in which the sensitivity of the estimate of the check depth to the noise in the raw data was reduced by making a large number of peak measurements (Figure 11) and characterizing the check using the approach illustrated in Figure 12.

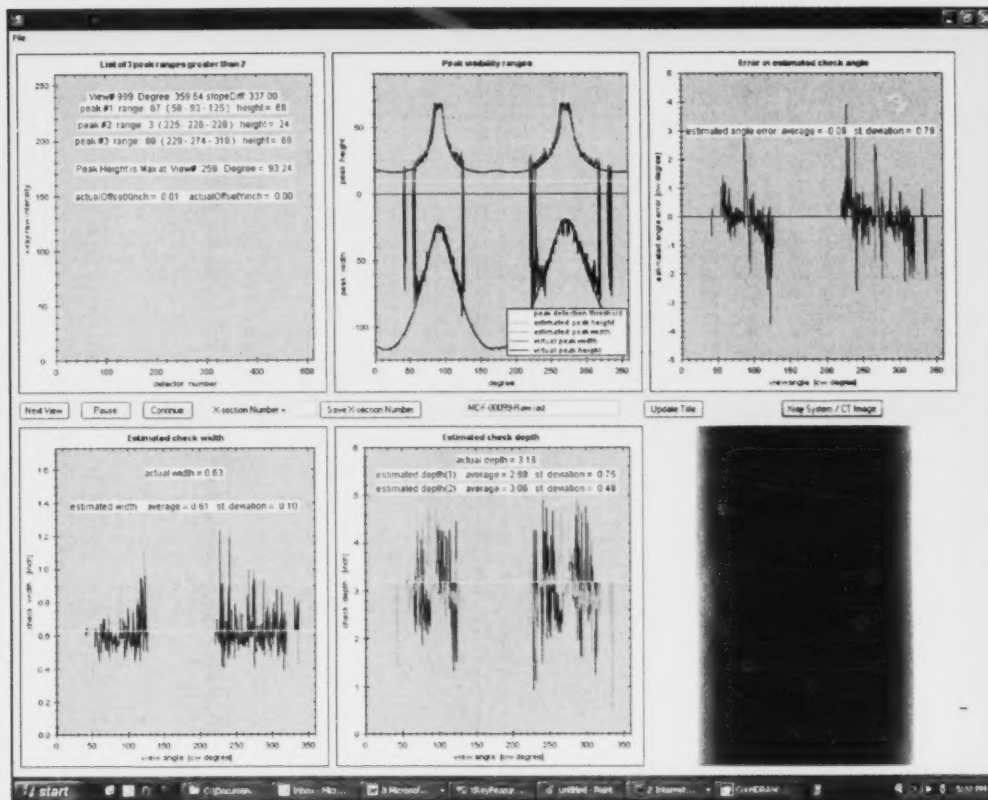


Figure 10. Views of the image processing application's screen with the summary of results for 10" diameter MDF disc.

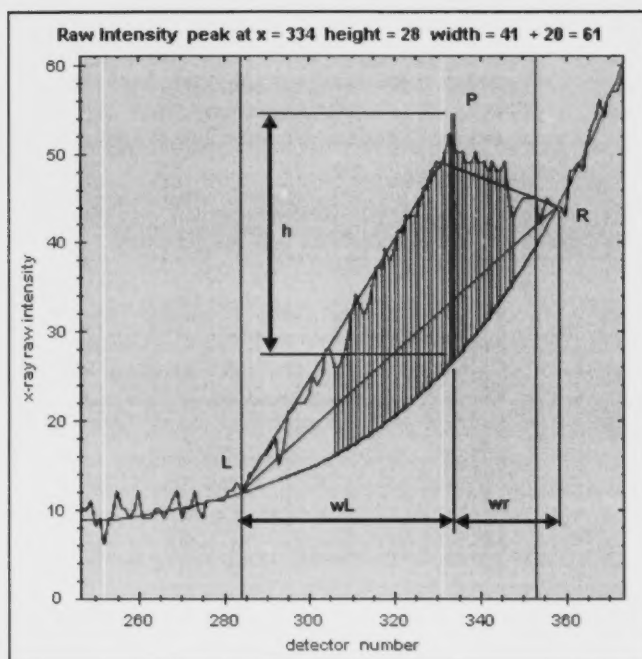


Figure 11. Quantifying the peak shape by a set of peak heights.

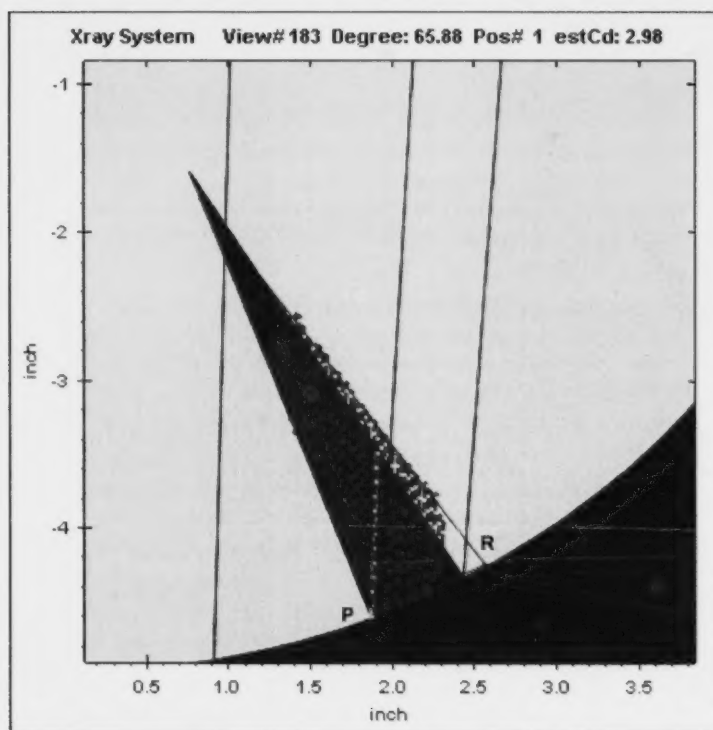


Figure 12. Characterizing the check shape using a set of check gaps. Yellow: log cross-section. Black wedge: an actual check. Red: check gaps.

Figure 12 shows part of a cross-section of the 10" diameter MDF disc when it was imaged by an X-ray scanner. The disc cross-section includes an actual check. The new algorithm relates the raw data in Figure 11 with the actual disc cross-section as follows:

- Using the X-ray attenuation equation, the set of peak heights was transformed into the magnitudes of the check gaps in Figure 12. The X-ray passing through the peak maximum point P in the raw data (Figure 11) intersects the log surface and represents the largest gap of the check model. Using simple 2-D geometry equations, an axis of the model check was defined, with the axis passing through the pith and defining the check's angular orientation. The check gaps then oriented along the X-rays to which they correspond and are appropriately positioned relative to the model check axis. The check gaps are shown as nearly vertical dashed red lines.
- Two least square lines are fitted to the end points of the check gaps. The intersection of these two lines defines the root of the (model) check, and the intersections of the two lines with the log cross-section's surface define the check mouth points P and R , and thus the check width.

The sensitivity of this algorithm to the noise in the X-ray detector raw data was studied analytically and experimentally to quantify the accuracy (d_{err}) with which this algorithm can estimate check depth (d_{est}) depending on the log diameter, the check depth (d), width (w), and angle (a) relative to the direction of X-rays; and the average error of estimated check gaps (e). Equation 2 relates these parameters for a 10-inch diameter log as:

$$d_{err} = d_{est} - d = (0.0159dae)w^{-1.07082} \quad [2]$$

For logs of different diameters, the above equation would include different numerical constants. It would be feasible to determine the "numerical constants" for other diameters and to use these constants to develop an equation such as Equation 2, but which would include the log diameter D explicitly. This was not completed during this project because of time and resource limitations.

2.1.3 Multiple checks in one log cross-section

When a log cross-section includes several checks, there are as many peaks in the raw data. The separation of the peaks in the raw data depends on the orientation of the checks relative to the X-rays; the visibility of each check is given by Equation 1. If the checks are visible and the corresponding peaks in the raw data are widely separated it is possible to characterize these checks as described above. If the checks are visible and the corresponding peaks in the raw data are not widely separated it would be very difficult or impossible to characterize such checks. In this project no software was developed to deal with multiple checks in one log cross-section.

2.1.4 Effects of knots and other defects

Processing of radiographs of cookies obtained from beetle-affected logs has shown that the checks may be detected and characterized in cookies that have a uniform or a slowly varying density distribution. When the cookies included defects such as knots or other localized areas of different density, such as iced or wet parts of the log surface, it made automated check detection and characterization very difficult or impossible. The defects may distort the raw data plots and produce multiple peaks and valleys from which the peak(s) caused by checks are difficult to single out and measure with any robustness.

2.1.5 Direct radiographs

A direct radiograph is the term used here to describe a set of contiguous radiographs such as those produced by an X-ray scanner when a log is conveyed through it. An example of a direct radiograph of an beetle-affected log containing checks is shown in Figure 13.

The top of Figure 13 shows the direct radiograph of a log with the raw data as provided by the X-ray detectors, with 1.0 cm spacing between the radiographs along the log length. Each radiograph is a thin vertical line with the grey scale variation of the raw data. In this case the log is approximately 500 cm long and hence the direct radiograph consists of a set of 500 radiographs providing an apparently seamless image of the log, such as would be produced by a conventional 2D X-ray machine.

The bottom of Figure 13 shows the direct radiograph of the same log after image processing software was used to increase the visibility of the checks and knots by enhancing the contrast of the image. Note that because the log has spiral grain the checks are most visible in the center of the log where the checks are parallel to the X-rays. Figure 14 shows the CT images of log cross-sections at points F and G on the log.

The investigation completed to this point determined how well visible checks would be characterized in one direct radiograph such as in Figure 13.

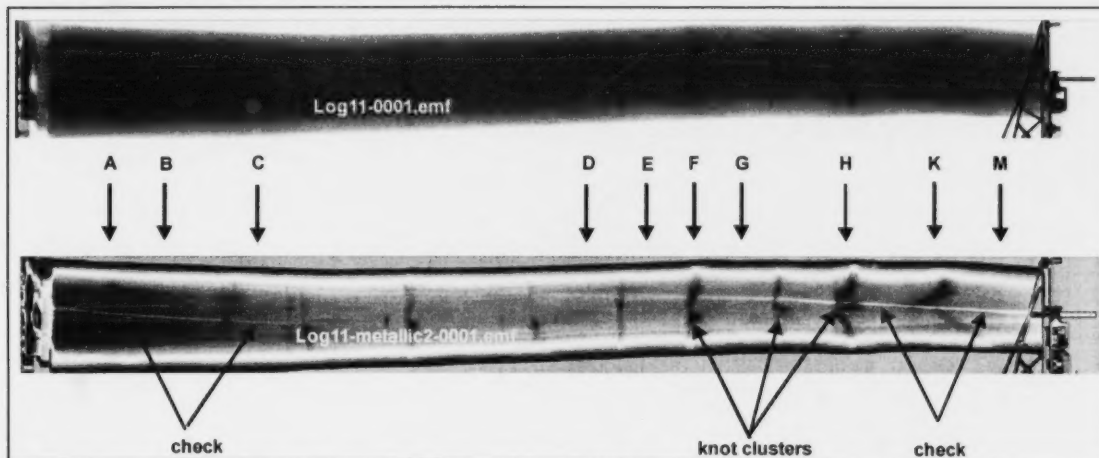


Figure 13. Direct radiographs of a beetle-affected log containing checks.

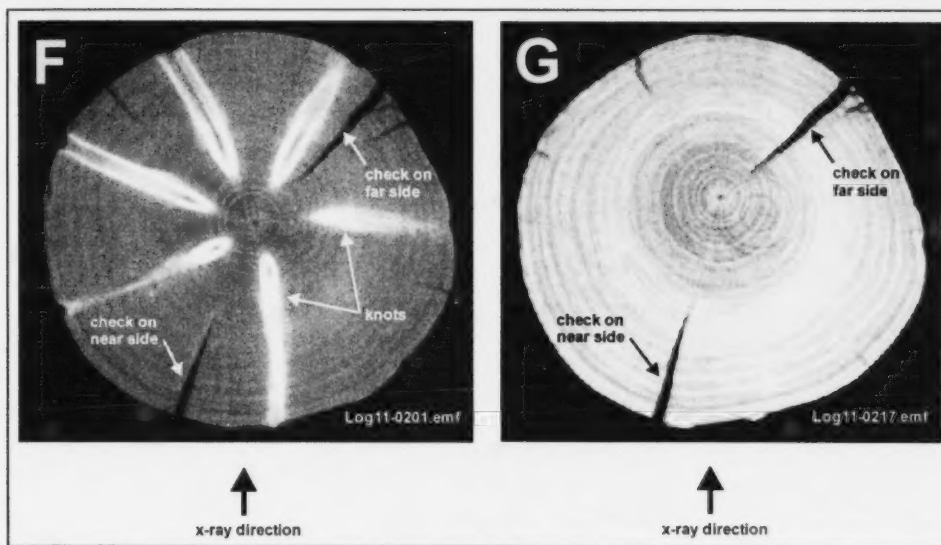


Figure 14. CT images of points F and G in Figure 13.

2.2 Detecting and characterizing checks in direct radiographs produced by a multi-view X-ray scanner

There are two critical items that cannot be determined from one direct radiograph: whether the check is facing toward or away from the X-ray source (i.e., on which side of the log is the check located), and whether the log has checks that are not visible in that particular direct radiograph. The need to resolve the two items necessitates the use of a multi-view X-ray scanner. The checks not visible in one view may be visible in other views. When a check is visible in at least two views, triangulation can be used to determine on which side of the log the check is located.

To appreciate how the visibility of a check depends on its orientation and thus varies in each view of a multi-view X-ray scanner, Figures 15 to 17 show direct radiographs of a checked log. Three views are shown, i.e., at 0°, 120°, and 240°, with CT images of several log cross-sections along the log length. This particular log has one large check and one smaller check with the orientation of both varying along the log length because of moderate grain twist. Figure 15 shows the view at 0°. No checks are clearly visible to the human eye or to the image processing software because the checks were oriented at large angles relative to the direction of the X-rays (red arrow).

Figure 16 shows the view at 120°. The large check is clearly visible from 70 to 230 inches. Note the discontinuity (i.e., “jump”) of this check at 150 inches. The smaller check is visible from 0 to 70 inches. When this image was magnified, the checks became visible in some knot clusters and invisible in others.

Figure 17 shows the view at 240°. The large check is clearly visible only from 0 to 50 inches but the smaller checks are not visible at all. More views would provide additional information about the checks in other portions of the log.

Figure 18 shows the image processing tasks used to detect checks in a direct radiograph.

The procedure for measuring a check is:

Task 1. The intervals along the log length in which the knot clusters occur are identified.

In Figure 18 these intervals are shown by red-edged rectangles numbered 1 through 14. These intervals could be identified by, for example, recognizing that the average grey scale of the radiographs including knots is significantly darker (here) than the grey scale of the radiographs of knot-free cross-sections.

Task 2. The location of the pith (point) in each knot cluster is estimated using the fact that the knots originate at the pith (Figure 19).

A smooth spline may be fitted to the pith points and used to define the pith at all other log cross-sections. The pith point location is needed in calculations of the check depth, etc.

Task 3. The “partial” checks are detected in the log sections that are free of knots, using image processing algorithms such as described in the previous sections.

In Task 4 the “partial” checks are “connected” into the complete checks along the length of the log image in the direct radiographs. The image processing algorithm would need to be developed, but it should not be difficult to do.

Task 4. Triangulation is used to determine which side of the log has the check.

Additional heuristic rules may be used to deal with the checks that are visible only in one view and extending the checks past their visible ends. It is desirable to characterize the checks as completely as possible and use all the available information about the checks to create models that closely approximate the actual logs. Such models are required for accurate optimization of log sorting and breakdown.

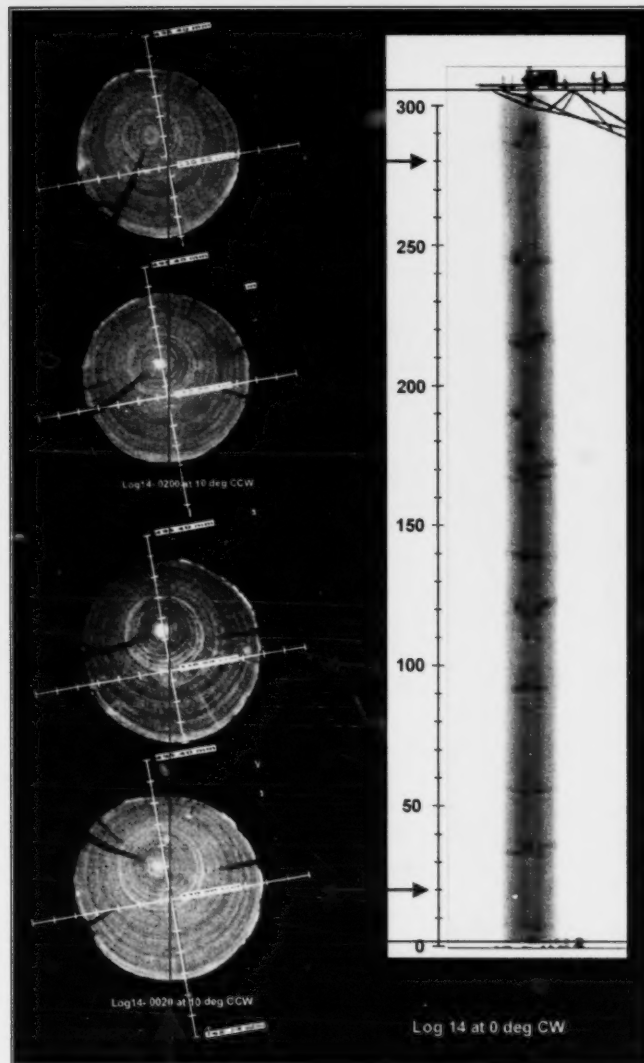


Figure 15. CT and direct radiograph images of a beetle-killed log in the 0° view.

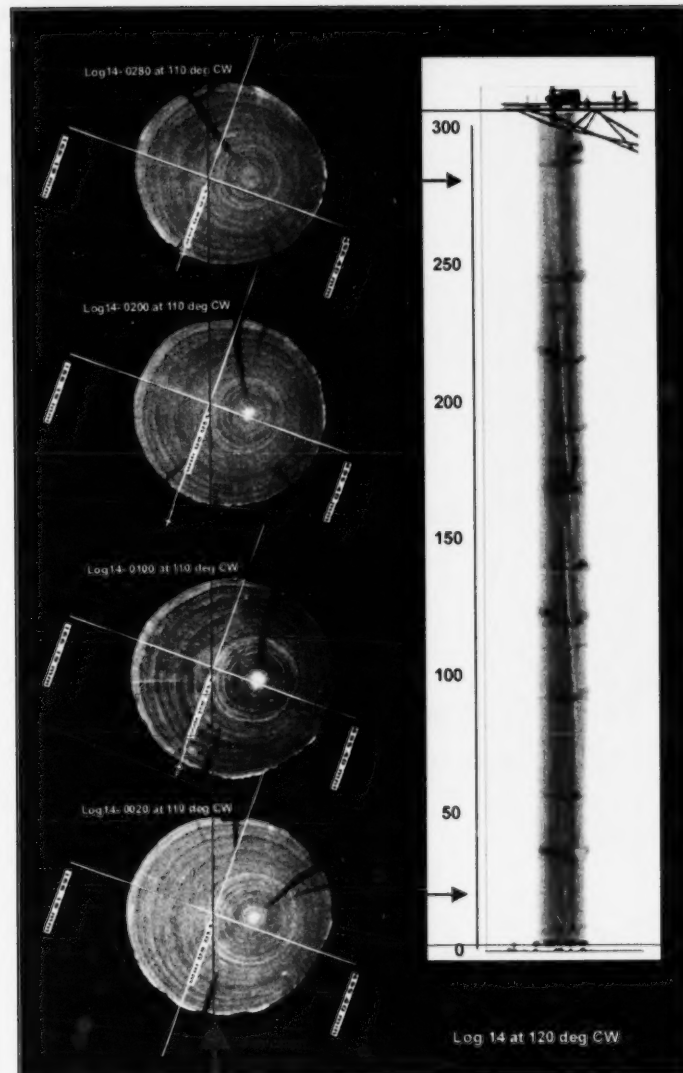


Figure 16. CT and direct radiograph images of a beetle-affected log in the 120° view.

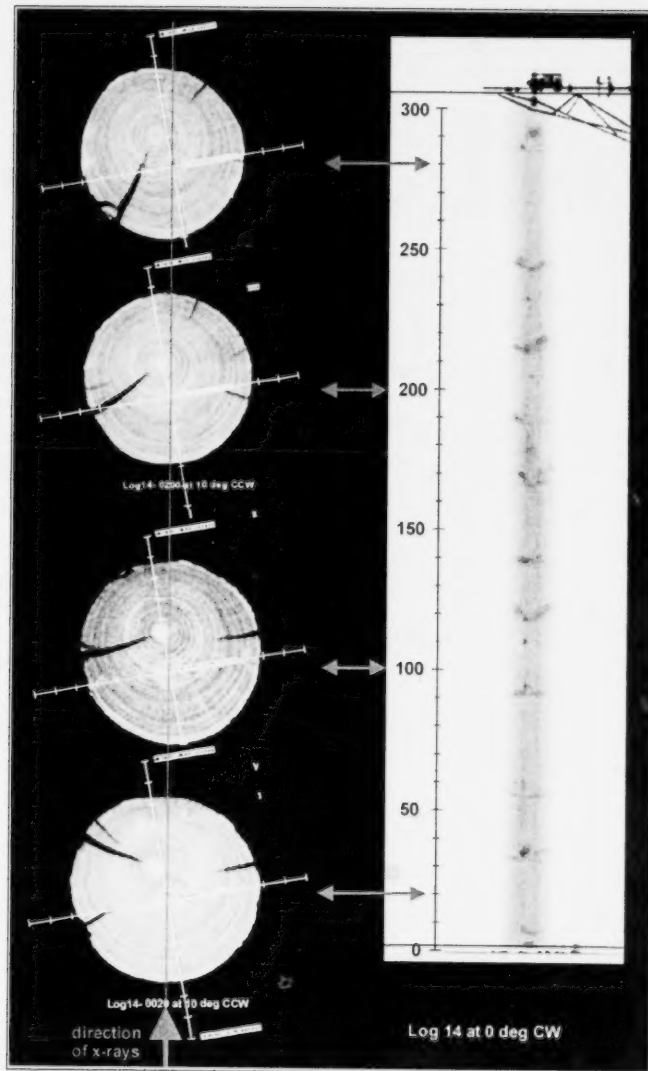


Figure 15. CT and direct radiograph images of a beetle-killed log in the 0° view.

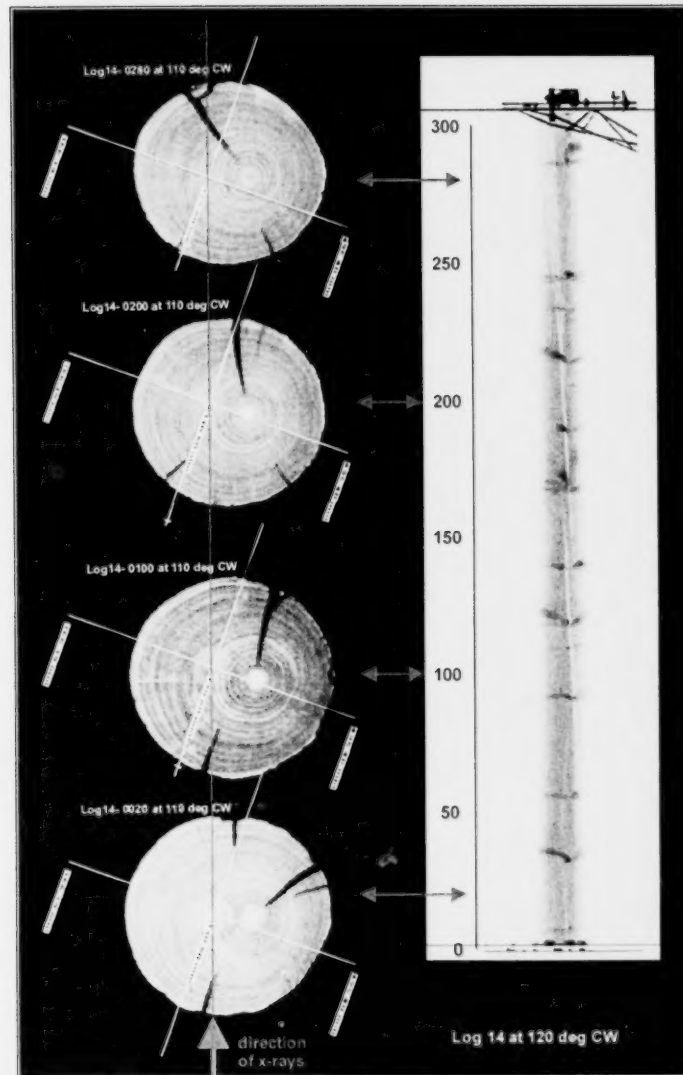


Figure 16. CT and direct radiograph images of a beetle-affected log in the 120° view.

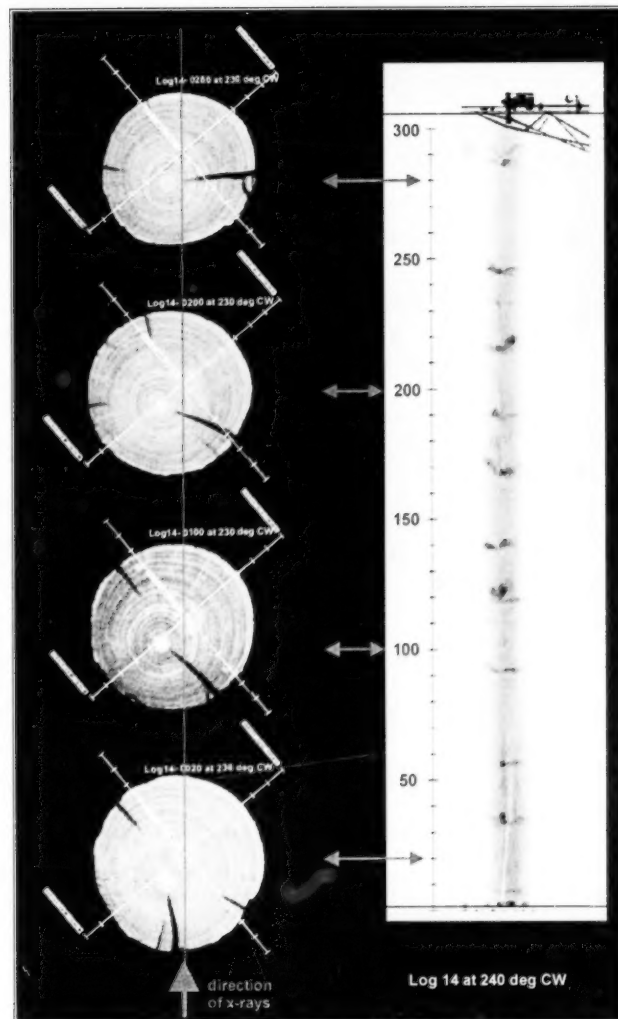


Figure 17. CT and direct radiograph images of a beetle-affected log in the 240° view.

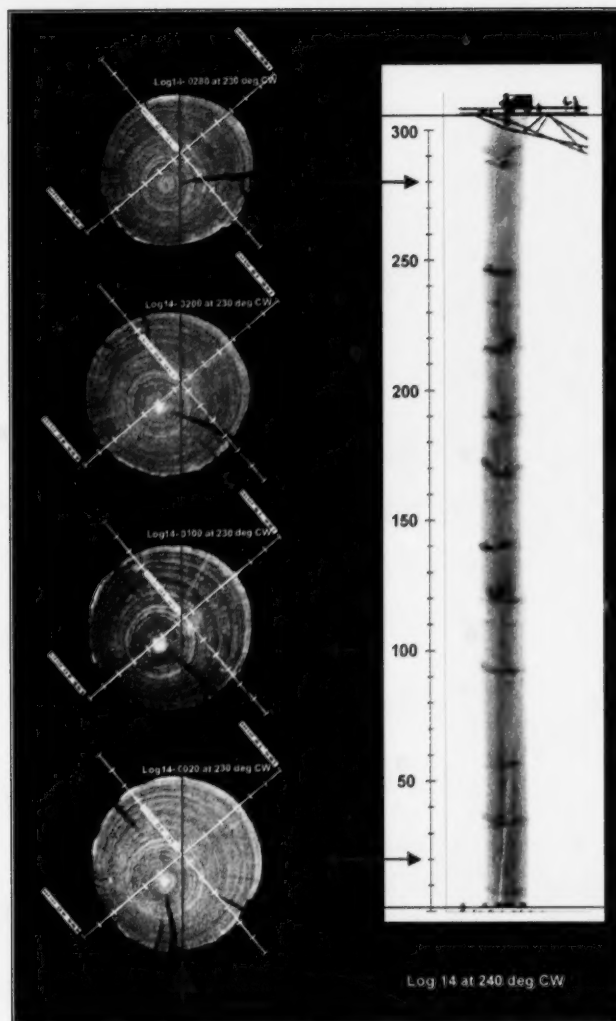


Figure 17. CT and direct radiograph images of a beetle-affected log in the 240° view.

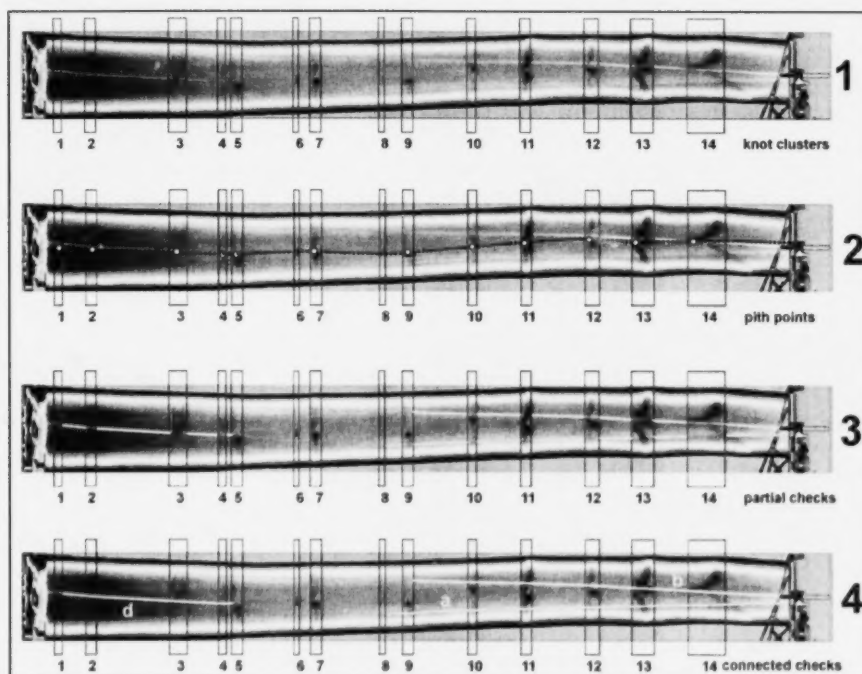


Figure 18. Image processing Tasks 1 to 4 were used to detect checks in a direct radiograph.
Note: Task 1 - Identify knot clusters; 2 - Locate pith points; 3 - Detect partial checks; 4 - Connect the checks

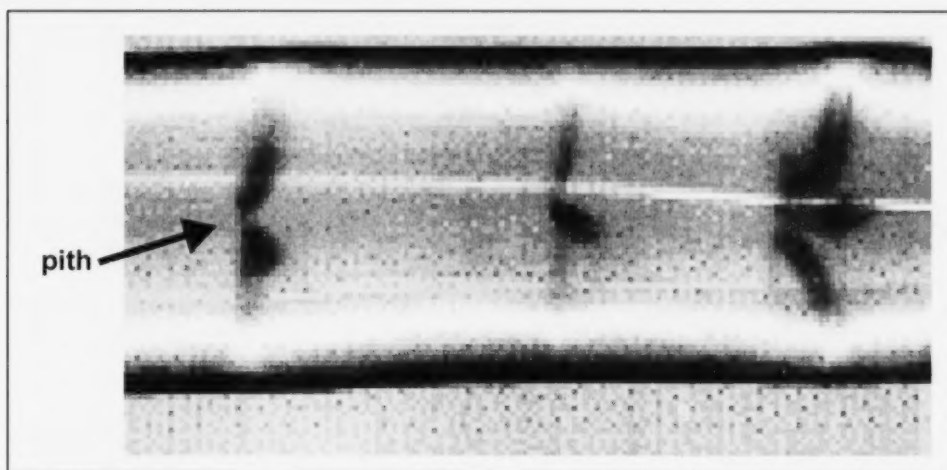


Figure 19. Detecting pith points in direct radiographs (Task 2).

2.3 Combining laser and multi-view X-ray scanning systems

Multi-view X-ray scanners cannot measure the shape of log cross-sections with the accuracy of true-shape laser scanners. But they can, in each view, detect log edges by acting as “shadow” scanners, and thus enable the creation of a polygon enclosing the shape of the log cross-section. A smooth “oval” can be “fitted” into the polygon to provide an approximate shape of the log cross-section. This approximate shape of the log cross-section may be adequate for check characterization, but is certainly not adequate for accurate optimization of log sorting and breakdown.

Furthermore, because the log may rock as it is crossing the gap between the in-feed and out-feed conveyors, the log shape that would be defined by the approximate cross-sections provided by an X-ray

scanner would be distorted. For these reasons multi-view X-ray scanners are used in combination with true-shape laser scanners, which record the shape of the log accurately while the log is transported on the in-feed conveyor with minimal bouncing.

The checks detected and characterized by multi-view X-ray scanners would be inserted into the true-shape of the log to facilitate accurate optimization of log sorting and breakdown by creating models of logs closely approximating the actual logs.

This project did not investigate the potential, in terms of more accurate check characterization, of providing images of log cross-sections obtained by (upstream) true-shape laser scanners to multi-view X-ray scanners.

2.4 Minimum technical requirements for a practical online X-ray scanner

The investigation described so far quantified the check visibility angles and the accuracy with which the visible checks can be characterized. Using this information it is possible to determine, for an X-ray scanner with specified number of views, the width of the narrowest check that would be visible in at least two views, regardless of check orientation. Alternatively, it is possible to determine the required number of views that an X-ray scanner needs to detect checks of specified the width in at least two views. Figure 20 shows the relationship between the number of views of an X-ray scanner and the width of the narrowest check that can be detected over the entire surface of the log cross-section.

The curves in Figure 20 are based on Equation 1 for estimating the visibility of checks. As the figure shows, and taking into consideration the accuracy with which the checks can be characterized, and the preliminary results of OPTITEK[®] simulations, it is obvious that an X-ray scanner with as many views as technically feasible would be desirable. Therefore, an X-ray scanner with six views was considered in this project, as that is the largest number of views commercially available. A schematic drawing of such a scanner is shown in Figure 21. The rationale was to determine the return on investment of this system and thus quantify the need for an X-ray scanner with more or fewer views.

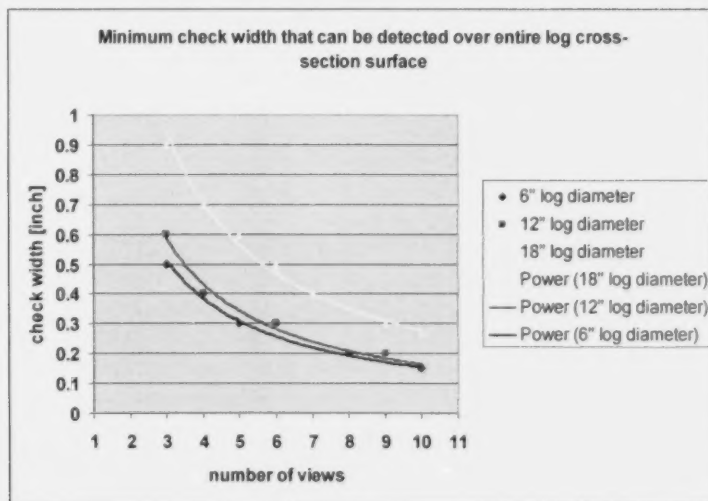


Figure 20. Minimum check width that can be detected by an X-ray scanner.

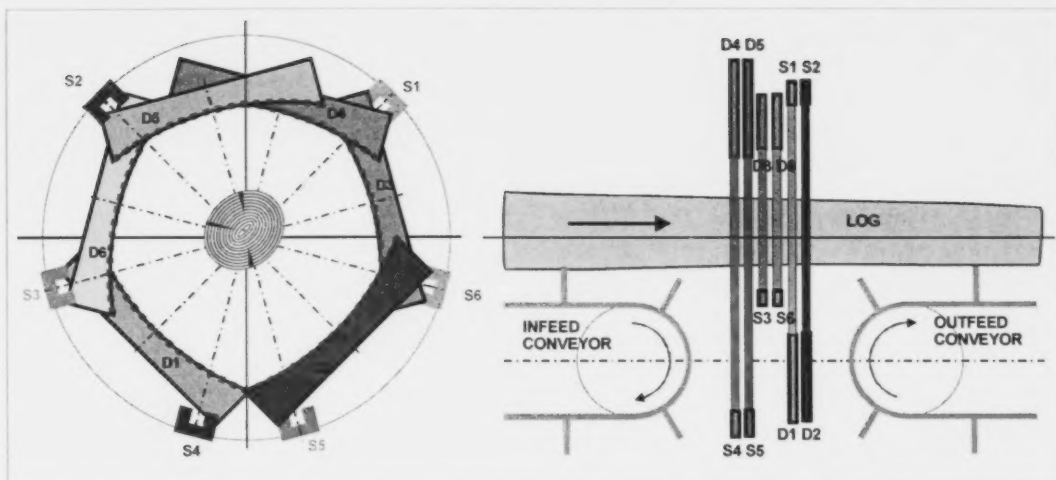


Figure 21. Schematic drawing of an X-ray scanner with six views (S1 to S6: X-ray sources; D1 to D6: detector assemblies).

Figure 21 shows the approximate positions of the six X-ray sources ...and detector assemblies. Each assembly is positioned so that logs of all required diameters are optimally scanned. The assemblies are oriented at carefully chosen angles to evenly distribute the six views over the 360° range. The sources and detectors are housed in metal enclosures that afford protection from bark and debris, and the entire scanner is within a lead-lined enclosure to protect workers from exposure to radiation.

To preclude X-rays emitted from one source reaching detectors associated with other sources, and for other considerations, the six assemblies are "stacked" next to each other in separate planes. Each assembly is approximately 3 inches thick, for a total of 18 inches along the z axis. A gap larger than this length is required between the in-feed and out-feed conveyors to allow unobstructed passage of the X-rays between the sources and the detectors. One undesirable consequence of the gap is that when the logs cross the gap, they may randomly rock or roll, which distorts the shape of the logs in the radiographs.

2.5 Determining the increase in lumber value recovery and return on investment

To determine the potential increase in the value of lumber recovery that could be achieved by deploying an X-ray scanner system, and to estimate the return on investment, the following tasks were required:

- Develop scenarios for applying an X-ray scanner, and investigate where, how, and for what purpose (i.e., optimal log sorting and/or breakdown) such a scanner would be incorporated into a sawmill operation.
- Create a database of log models for the breakdown simulation in the above scenarios.
- Develop an OPTITEK® model of a typical Interior British Columbia sawmill that processes beetle-affected logs (see Appendix C for details).
- Determine the value recovery from each sample log in the above scenarios.
- Using the sample logs as the basis, create log supplies that are a mix of healthy logs, beetle-affected logs, and pulp logs.
- Determine the value recovery increase for each scenario. The baseline scenario is the current sawmill operation.
- Estimate the return on investment from the deployment of an X-ray scanner system.

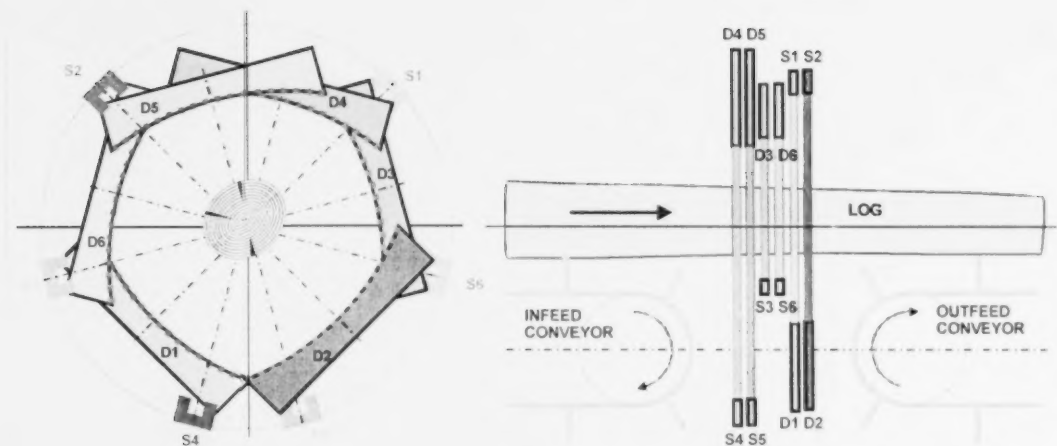


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To preclude X-rays emitted from one source reaching detectors associated with other sources, and for other considerations, the six assemblies are “stacked” next to each other in separate planes. Each assembly is approximately 3 inches thick, for a total of 18 inches along the z axis. A gap larger than this length is required between the in-feed and out-feed conveyors to allow unobstructed passage of the X-rays between the sources and the detectors. One undesirable consequence of the gap is that when the logs cross the gap, they may randomly rock or roll, which distorts the shape of the logs in the radiographs.

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- Determine the value recovery increase for each scenario. The baseline scenario is the current sawmill operation.
- Estimate the return on investment from the deployment of an X-ray scanner system.

2.5.1 Log supply database

To get the best representation of beetle-affected log supplies, the largest possible sample size was used (Table 2), as determined by the estimated time and cost involved in processing the OPTITEK® studies.

The log lengths ranged from 10 to 16 ft. The log shape data were provided by modern, true-shape laser scanners.

2.5.1.1 Checked Logs

Time since the death of the tree, as caused by the mountain pine beetle, was estimated to be 3 to 5 years.

All sample logs had checks. The approximate number and characteristics of the logs in the samples from each diameter class were selected as follows:

- 40% of the logs contained one check at least 1 inch deep and 4 ft long.
- 60% of the logs contained two or more checks, all at least 1 inch deep and 4 ft long.
- Of the above logs, at least 10% had severe twist (spiral grain).
- logs were of random lengths and sweep.

Check width, depth, and location were measured manually and the accuracy of measurements were validated using the CT scanner. The summary of shape and check data is in Appendix B.

2.5.1.2 Healthy Logs and Pulp Logs

The log diet of a sawmill consists of a mix of healthy (unchecked) logs, beetle-affected logs, and pulp (reject) logs. Instead of collecting separate data for healthy and pulp logs, the log models of the checked logs were reused by excluding the checks. in the OPTITEK® study.

Since OPTITEK® does not process pulp logs, they were converted to the appropriate volume of chips.

Table 2. Description of sample log supply.

Diameter class ^a	Diameter range (inches)	Logs in simulation (no.)	Portion of log supply (%)
1	<7	67	0.23
2	7 to 10	59	0.34
3	10 to 13	62	0.24
4	13 to 16	<u>58</u>	0.19
		246	

^a Based on large-end diameters.

2.5.2 Creating beetle-affected log supplies

No data for an entire beetle-affected log supply—i.e., consisting of various proportions of healthy, checked, and reject logs—were available. To complicate matters further, the degree of checking in the log supply varied. This meant that the simulation had to categorize the check severity in the sample logs and also in the log supply.

Check severity categories for logs were developed as follows:

1. The logs in the database were processed through OPTITEK® to obtain the lost value due to the checking (\$/m³).
2. For each diameter class, the logs were sorted by lost value.
3. The range of lost value was divided into three equal categories. Logs with the lowest value loss were labelled Lightly Checked. The other categories were Medium Checked and Severely Checked (Table 3).

Note that each diameter class had different value loss thresholds for the three categories of check severity. This was not ideal, but until better data are available, it is a simple model that is easily comprehended.

This measure of check severity was used because no standard method exists of measuring or quantifying it based on physical check characteristics. Furthermore, describing check severity in monetary terms

(\$/m³) is useful for the economic evaluation done here; it would also be the best criterion for differentiating between saw logs and pulp logs in sorting applications.

The second stage of developing the log supply database involved defining three levels of check severity that apply not just to logs but to the whole log supply. Again, due to lack of data, assumptions were made about the proportions of healthy, checked, and reject logs (Table 4).

2.5.3 Scenarios of implementing X-ray scanning of logs

High costs and complicated operational requirements make it impractical to use a multi-view X-ray scanner in the forest or in remote log yards. However two other scenarios for using an X-ray scanner to characterize logs are proposed:

1. In a log-sorting facility (Figure 22), which could be in the millyard or at a central sortyard.
2. Installed in the front end of a sawmill and integrated with the existing log turner and with the scanning and optimization system (Figure 23).

These scenarios are discussed in greater detail in Appendix D.

Table 3. An example of how the sample logs were divided into three categories: Lightly Checked, Medium Checked, and Heavily Checked.

diameter class	log sequence	log#	Pulp logs			CM - healthy logs			CM - checked logs			
			TotVol (m3)	Val/lg (\$/lg)	Val/lg (\$/lg)	Val/Vnm (\$/m3)	Val/lg (\$/lg)	Val/Vnm (\$/m3)	type	TotVol (m3)	TotVal (\$)	AveVal (\$/m3)
1	1	51	0.13	2.08	12.19	98	10.86	87	lightly checked	2.08	171.90	82.77
	2	52	0.13	2.08	12.19	98	10.86	87				
	3	21	0.14	2.27	15.04	110	12.96	95				
	4	62	0.10	1.66	10.90	109	9.02	91				
	5	64	0.10	1.66	10.90	109	9.02	91				
	6	28	0.13	2.24	13.07	97	10.67	79				
	7	50	0.13	2.08	12.19	98	9.83	79				
	8	16	0.11	1.84	12.27	111	9.57	87				
	9	18	0.11	1.84	12.27	111	9.57	87				
	10	19	0.11	1.84	12.27	111	9.57	87				
	11	20	0.14	2.27	15.04	110	11.68	86				
	12	23	0.14	2.27	15.04	110	11.27	83				
	13	43	0.08	1.28	7.45	97	5.58	72				
	14	30	0.10	1.69	9.91	98	7.28	72				
	15	67	0.09	1.50	9.35	104	6.84	76				
	16	17	0.11	1.84	12.27	111	8.86	80				
	17	14	0.07	1.16	7.74	111	5.37	77				
	18	15	0.07	1.16	7.74	111	5.37	77				
	19	58	0.11	1.80	11.14	103	7.72	72				
	20	31	0.10	1.69	9.91	98	6.70	66	medium checked	3.25	186.98	57.61
	21	49	0.13	2.08	12.19	98	8.16	65				
	22	37	0.08	1.37	8.09	98	5.39	65				
	23	8	0.13	2.14	13.34	104	8.72	68				
	24	33	0.10	1.69	9.91	98	6.46	64				
	25	53	0.08	1.41	9.21	109	5.80	68				
	26	1	0.10	1.61	10.83	112	6.80	70				
	27	11	0.11	1.86	11.61	104	7.25	65				
	28	26	0.11	1.80	10.05	93	6.08	56				
	29	32	0.10	1.69	9.91	98	5.88	58				
	30	61	0.10	1.66	10.90	109	6.36	64				
	31	65	0.09	1.50	9.35	104	5.32	59				
	32	12	0.07	1.16	7.74	111	4.32	62				
	33	13	0.07	1.16	7.74	111	4.32	62				
	34	59	0.11	1.80	11.14	103	6.08	56				
	35	29	0.13	2.24	13.07	97	7.05	52				
	36	6	0.13	2.14	13.34	104	7.15	56				
	37	3	0.10	1.61	10.83	112	5.76	59				
	38	4	0.10	1.61	10.83	112	5.76	59				
	39	2	0.10	1.61	10.83	112	5.76	59				
	40	22	0.14	2.27	15.04	110	7.84	57				
	41	63	0.10	1.66	10.90	109	5.54	56				
	42	34	0.08	1.37	8.09	98	4.06	49				
	43	35	0.08	1.37	8.09	98	4.06	49				
	44	36	0.08	1.37	8.09	98	4.06	49				
	45	7	0.13	2.14	13.34	104	6.64	52				
	46	42	0.08	1.28	7.45	97	3.70	48				
	47	38	0.07	1.12	6.77	101	3.35	50				
	48	57	0.11	1.80	11.14	103	5.36	50				
	49	60	0.11	1.80	11.14	103	5.36	50				
	50	5	0.13	2.14	13.34	104	6.40	50				
	51	10	0.11	1.86	11.61	104	5.49	49	severely checked	1.38	53.44	38.74
	52	27	0.11	1.80	10.05	93	4.75	44				
	53	44	0.08	1.28	7.45	97	3.35	43				
	54	41	0.08	1.28	7.45	97	3.23	42				
	55	45	0.08	1.29	8.51	110	3.67	47				
	56	46	0.08	1.29	8.51	110	3.67	47				
	57	66	0.09	1.50	9.35	104	4.01	45				
	58	56	0.08	1.41	9.21	109	3.88	46				
	59	9	0.11	1.86	11.61	104	4.78	43				
	60	39	0.07	1.12	6.77	101	2.57	38				
	61	24	0.11	1.80	10.05	93	3.72	34				
	62	54	0.08	1.41	9.21	109	3.10	37				
	63	47	0.08	1.29	8.51	110	2.74	35				
	64	48	0.08	1.29	8.51	110	2.74	35				
	65	25	0.11	1.80	10.05	93	3.01	28				
	66	40	0.07	1.12	6.77	101	1.84	27				
	67	55	0.08	1.41	9.21	109	2.38	28				

Table 4. Volume percentages of healthy, checked, and pulp (reject) logs in log supply.

Level of checking in log supply	Healthy logs (%)	Categories of logs with checks			Pulp logs (%)	Total (%)
		Lightly Checked (%)	Medium Checked (%)	Severely Checked (%)		
Light	30	40	20	9.5	0.5	100
Medium	20	30	30	18.5	1.5	100
Severe	5	20	40	33.0	2	100

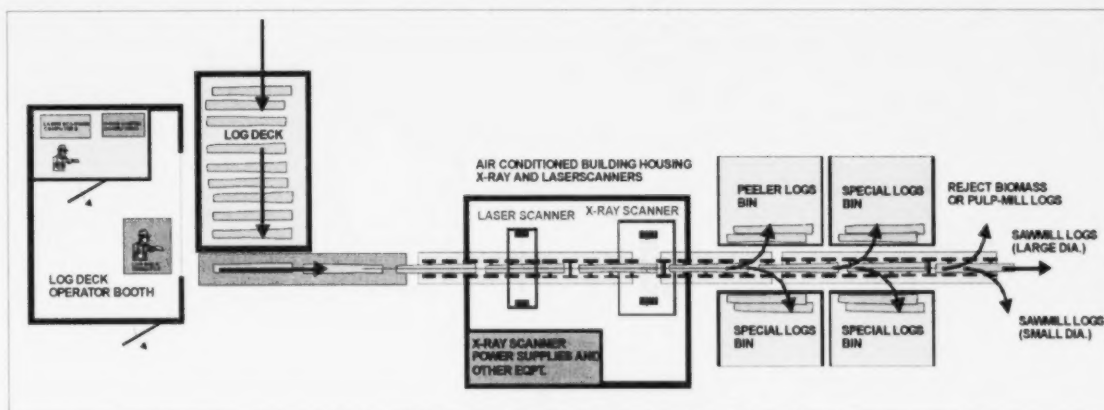


Figure 22. Schematic of a log yard sorting facility that includes an X-ray scanner.

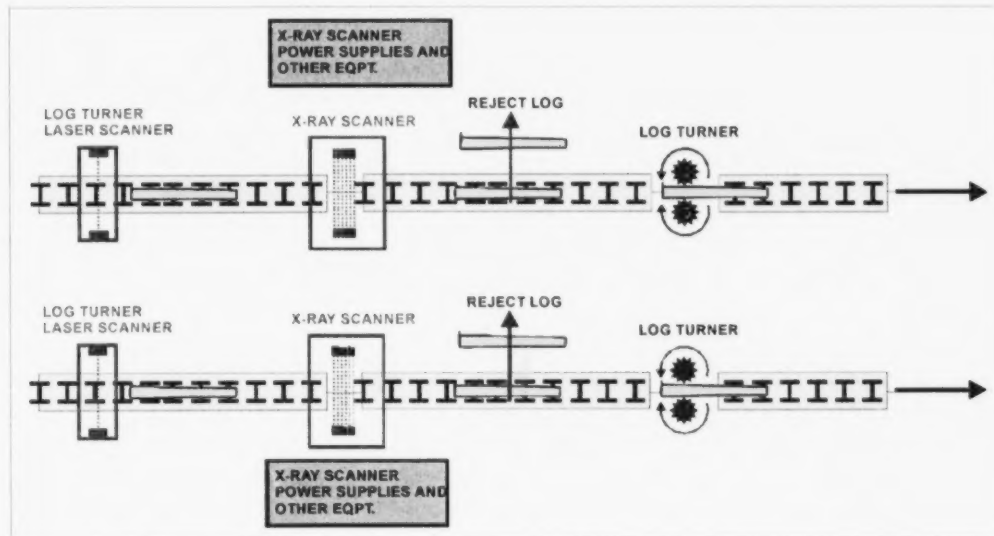


Figure 23. Schematic of the front end of sawmill using X-ray scanners.

Table 3. An example of how the sample logs were divided into three categories: Lightly Checked, Medium Checked, and Heavily Checked.

diameter class	log sequence	log#	Pulp logs		CM - healthy logs			CM - checked logs				
			TotVol (m3)	Val/fg (\$/g)	Val/fg (\$/g)	Val/Vnm (\$/m3)	Val/fg (\$/g)	Val/Vnm (\$/m3)	type	TotVol (m3)	TotVal (\$)	AveVal (\$/m3)
1	1	51	0.13	2.08	12.19	98	10.86	87	lightly checked	2.08	171.90	82.77
	2	52	0.13	2.08	12.19	98	10.86	87				
	3	21	0.14	2.27	15.04	110	12.96	95				
	4	62	0.10	1.66	10.90	109	9.02	91				
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	6	28	0.13	2.24	13.07	97	10.67	79				
	7	50	0.13	2.08	12.19	98	9.83	79				
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	11	20	0.14	2.27	15.04	110	11.68	86				
	12	23	0.14	2.27	15.04	110	11.27	83				
	13	43	0.08	1.28	7.45	97	5.58	72				
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	19	58	0.11	1.80	11.14	103	7.72	72				
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	23	8	0.13	2.14	13.34	104	8.72	68				
	24	33	0.10	1.69	9.91	98	6.46	64				
	25	53	0.08	1.41	9.21	109	5.80	68				
	26	1	0.10	1.61	10.83	112	6.80	70				
	27	11	0.11	1.86	11.61	104	7.25	65				
	28	26	0.11	1.80	10.05	93	6.08	56				
	29	32	0.10	1.69	9.91	98	5.88	58				
	30	61	0.10	1.66	10.90	109	6.36	64				
	31	65	0.09	1.50	9.35	104	5.32	59				
	32	12	0.07	1.16	7.74	111	4.32	62				
	33	13	0.07	1.16	7.74	111	4.32	62				
	34	59	0.11	1.80	11.14	103	6.08	56				
	35	29	0.13	2.24	13.07	97	7.05	52				
	36	6	0.13	2.14	13.34	104	7.15	56				
	37	3	0.10	1.61	10.83	112	5.76	59				
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	54	41	0.08	1.28	7.45	97	3.23	42				
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	60	39	0.07	1.12	6.77	101	2.57	38				
	61	24	0.11	1.80	10.05	93	3.72	34				
	62	54	0.08	1.41	9.21	109	3.10	37				
	63	47	0.08	1.29	8.51	110	2.74	35				
	64	48	0.08	1.29	8.51	110	2.74	35				
	65	25	0.11	1.80	10.05	93	3.01	28				
	66	40	0.07	1.12	6.77	101	1.84	27				
	67	55	0.08	1.41	9.21	109	2.38	28				

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Medium	20	30	30	18.5	1.5	100
Severe	5	20	40	33.0	2	100

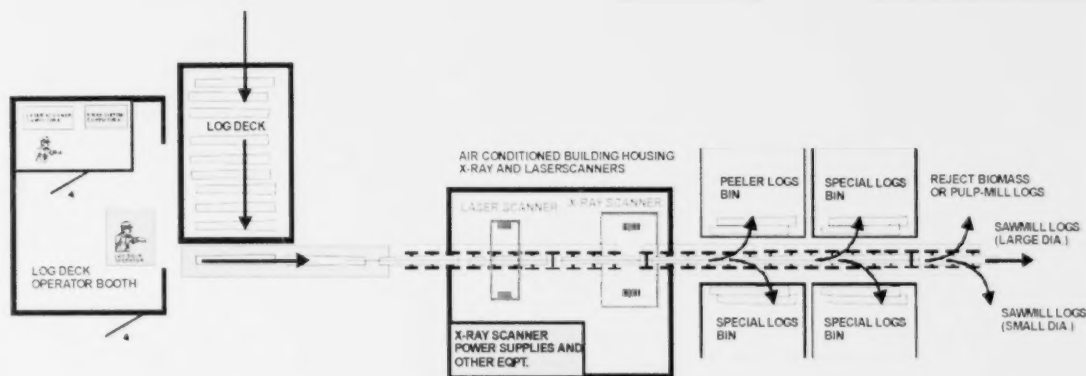


Figure 22. Schematic of a log yard sorting facility that includes an X-ray scanner.

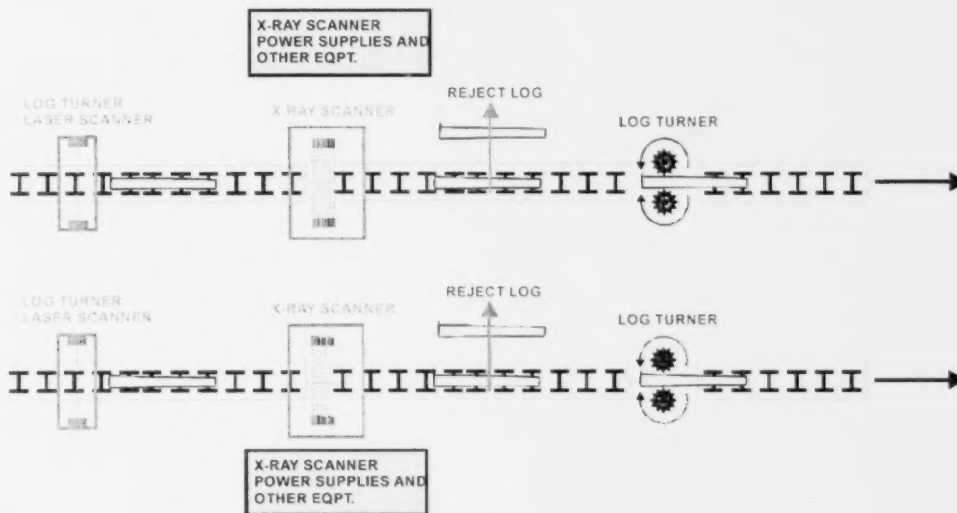


Figure 23. Schematic of the front end of sawmill using X-ray scanners.

2.5.4 Analysis

Scenarios have been designed for investigating how the major variables affect value recovery. The variables fall into two categories:

- *Technological*: related to the ability of equipment to find checks and process logs correctly.
- *Strategic*: introducing X-ray scanning allows for different strategies in sorting low-value logs and in optimizing value recovery in the breakdown stages.

There are three levels of X-ray scanning capability:

1. *None*: This is the current technology, which measures only external log shape without detecting checks.
2. *Perfect Check Knowledge*: All checks, of all sizes, are seen and measured accurately.
3. *Imperfect X-ray Scanner*: Some checks are seen and measured with limited accuracy. Scanning with a 6-head X-ray scanner is considered here to estimate both theoretical and expected implementation limitations of this type of scanner.

The performance of these three levels of X-ray scanning capability define upper and lower limits of what is possible with X-ray scanning and are used to estimate the performance range of commercial systems.

The optimal sawing pattern depends on the level of X-ray scanning capability and the severity of checking (see Appendix E for details). The degree to which the imperfect X-ray scanner can accurately find and characterize checks is defined as the percentage of the difference between the value recovered with no check information and the value recovered with perfect check information. This is a performance measure for the X-ray scanner, image interpretation software, and the optimization software.

For example:

Product value with perfect check information	\$15 000
Product value with no check information	\$10 000
Difference	\$ 5 000

Therefore the value recovery when using a 50% capable X-ray scanner is

$$\$10\,000 + 50\% \times \$5000 = \$12\,500.$$

2.5.5 Estimating value recovery

OPTITEK®, FPInnovations–Forintek’s sawmill simulation software, was used to model optimal log sorting and breakdown in the scenarios as described above. The output of each simulation was an estimate of the volume and value of the output products, including sawdust and chips, for each of the sample logs.

The spreadsheet calculations normally used to convert green lumber (as determined by the OPTITEK® simulation) into the planer mill output, and thus determine the finished lumber volume and value recoveries, were not used in this project because the green lumber volume and value recoveries were deemed sufficient to estimate the return on investment.

The value recoveries from the sample logs, for each log supply and scenario, were put into spreadsheets to accomplish the following:

- **Calculation of production and income on a sawmill shift basis.** Sawmill production and income were calculated using two spreadsheets.

The first spreadsheet, partly shown in Figure 24, “processed” 1000 m³ from the log supply. This volume consisted of logs of different types (healthy, lightly checked,..., pulp logs). The value from each sample log was obtained using volume weighting based on the log being sorted as a sawmill log, or as chips in a separate chipping facility when the log is sorted as a pulp log. Other uses for higher-valued non-sawmill logs, such as peeler logs, were not considered.

A second spreadsheet (not shown) was used to calculate the volume of the input log supply needed to maintain the sawmill’s current production volume per shift (here, 1852 m³/shift).

- **Log and lumber prices.** The cost of logs, delivered to the sawmill yard, was set at \$50/m³.

The lumber prices and byproduct prices were based on a 3-year average (2005 to 2007) at one fixed exchange rate. This period was one of enormous fluctuation, not only in lumber prices but in currency as well. (The rate of exchange for this period was set at roughly USD 0.80:CAD 1.00.) See Appendix F for the list of products and prices.

model sorting facility input log volume = 1000 (m³ / shift)

log volume distribution in mill log supply with light overall checking level								
log type			healthy	lightly checked	medium checked	severely checked	pulp	totals
specified subtotals (%)			30	40	20	9.5	0.5	100
subtotals (m3)			300	400	200	95	5.00	1000
input logs volume subtotals (m3)	d1	input logs	70	94	47	22	1.17	
	d2	input logs	102	136	68	32	1.70	
	d3	input logs	71	95	48	23	1.19	
	d4	input logs	56	75	37	18	0.94	
output logs volume subtotals (m3)	d1	sawmill logs	70	94	47	12	1.17	
		sort pulp logs		0	0	10		
	d2	sawmill logs	102	136	64	27	1.70	
		sort pulp logs		0	4	6		
	d3	sawmill logs	71	95	48	23	1.19	
		sort pulp logs		0	0	0		
	d4	sawmill logs	56	75	37	3	0.94	
		sort pulp logs		0	0	15		
volume totals of sawmill logs (m3)			300	400	196	65	5.00	966
volume totals of sort pulp logs (m3)				0	4	30		34
output logs value subtotals (\$)	d1	sawmill logs	7288	7745	2696	546	19	
		sort pulp logs		0	0	163		
	d2	sawmill logs	11992	13322	5205	1909	28	
		sort pulp logs		0	62	95		
	d3	sawmill logs	8741	10961	4771	1920	20	
		sort pulp logs		0	0	0		
	d4	sawmill logs	6628	7469	3343	203	16	
		sort pulp logs		0	0	247		
value totals of saw logs + sort pulp logs (\$)			34649	39497	16014	4578	83	94822

Figure 24. Example of a spreadsheet used to calculate sawmill production and income from 1000 m³ of logs

2.5.6 Incremental ROI from deployment of X-ray scanner

The potential returns associated with using X-ray technology at sawmills in the Interior of British Columbia was determined by calculating the incremental revenue minus incremental cost increase of using the X-ray scanner. The revenue from the "Current Mill scenario," which was called Current Mill Checked logs, was treated as the baseline. Revenues generated in other scenarios were compared to the Current Mill scenario to determine the incremental revenue gain or loss.

The cost side of the equation is reasonably well known. The current costs of operating a sawmill in the Interior of British Columbia have also been validated by industry members. The cost of implementing an X-ray scanner is quoted by an equipment supplier, Bintek Oy. The variable cost of the X-ray scanner was determined to be the cost of additional personnel, additional in-yard transport costs, and the cost of maintenance and spare parts. All of the information used in determining operational costs of the Current Mill and the incremental operational costs of running an X-ray scanning facility are in Table 5.

Note that this is not an exhaustive examination of the financial benefits of installing X-ray technology at a sawmill. For this project, log supplies and sorting strategies were generated merely to provide general trends and to show the potential of the technology.

- **Log and lumber prices.** The cost of logs, delivered to the sawmill yard, was set at \$50/m³.

The lumber prices and byproduct prices were based on a 3-year average (2005 to 2007) at one fixed exchange rate. This period was one of enormous fluctuation, not only in lumber prices but in currency as well. (The rate of exchange for this period was set at roughly USD 0.80:CAD 1.00.) See Appendix F for the list of products and prices.

model sorting facility input log volume = 1000 (m³ / shift)

log volume distribution in mill log supply with light overall checking level								
log type			healthy	lightly checked	medium checked	severely checked	pulp	totals
specified subtotals (%)			30	40	20	9.5	0.5	100
subtotals (m3)			300	400	200	95	5.00	1000
input logs volume subtotals (m3)	d1	input logs	70	94	47	22	1.17	
	d2	input logs	102	136	68	32	1.70	
	d3	input logs	71	95	48	23	1.19	
	d4	input logs	56	75	37	18	0.94	
output logs volume subtotals (m3)	d1	sawmill logs	70	94	47	12	1.17	
		sort pulp logs		0	0	10		
	d2	sawmill logs	102	136	64	27	1.70	
		sort pulp logs		0	4	6		
	d3	sawmill logs	71	95	48	23	1.19	
		sort pulp logs		0	0	0		
	d4	sawmill logs	56	75	37	3	0.94	
		sort pulp logs		0	0	15		
volume totals of sawmill logs (m3)			300	400	196	65	5.00	966
volume totals of sort pulp logs (m3)				0	4	30		34
output logs value subtotals (\$)	d1	sawmill logs	7288	7745	2696	546	19	
		sort pulp logs		0	0	163		
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		sort pulp logs		0	62	95		
	d3	sawmill logs	8741	10961	4771	1920	20	
		sort pulp logs		0	0	0		
	d4	sawmill logs	6628	7469	3343	203	16	
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value totals of saw logs + sort pulp logs (\$)			34649	39497	16014	4578	83	94822

Figure 24. Example of a spreadsheet used to calculate sawmill production and income from 1000 m³ of logs

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Note that this is not an exhaustive examination of the financial benefits of installing X-ray technology at a sawmill. For this project, log supplies and sorting strategies were generated merely to provide general trends and to show the potential of the technology.

In this study, logs were optimized for revenue, based on checking only. Current X-ray scanning facilities optimize logs based on a number of criteria (Appendix G) for increasing grade outturn—none of these criteria was considered in this study.

Table 5. Operational costs of the Current Mill, and incremental operational costs of an X-ray scanning facility.

Current Mill	\$/m ³	\$/mbf
Log handling	7	11
Sawmill	\$51	83
Kilns/energy	7	12
Planer	20	33
General plant	6	9
Delivered log	50	
X-ray facility		
Fixed costs		
X-ray facility, capital cost	\$9 700 000	
X-ray facility, capacity	2000 m ³ /shift	
Additional personnel	\$1 200/shift	
Variable costs		
Spare parts & maintenance	\$1 000/shift	
Additional log handling	\$6 500/shift	

3 Results

3.1 Ability of X-ray scanners to detect and characterize checks in beetle-affected logs

3.1.1 Check detection

The investigation showed that checks can be detected by an X-ray scanner. However, the scanner's performance will depend on the number of views it has, check width, and log diameter. Table 6 and Figure 25 show the total check visibility ranges (% of 360°) for logs and checks of various sizes. The visibility ranges are based on Equation 1.

Regardless of its orientation, a check is visible in at least one view when its visibility range is >100% of 360°, and in two views when its visibility range is >200% of 360°. As shown in Figure 25, narrower checks are generally only visible over parts of log cross-section and not visible in the gaps between.

Table 6. Visibility ranges* of checks for an X-ray scanner with six views.

log diameter	check width	scanner with one view			scanner with six views	
		near visibility range	far visibility range	total visibility range	total visibility range	total visibility range
(in)	(in)	(deg)	(deg)	(deg)	(% of 360)	(deg)
6	0.05	5	6	12	3	70
	0.10	11	13	23	7	141
	0.15	16	19	35	10	211
	0.20	22	25	47	13	282
	0.30	32	38	70	20	423
	0.40	43	51	94	26	564
12	0.50	54	63	117	33	705
	0.05	5	6	10	3	62
	0.10	9	12	21	6	123
	0.15	14	17	31	9	185
	0.20	18	23	41	11	247
	0.30	27	35	62	17	370
	0.40	36	46	82	23	493
	0.50	45	58	103	29	617
18	0.60	54	69	123	34	740
	0.70	63	81	144	40	863
	0.05	3	4	6	2	39
	0.10	5	8	13	4	78
	0.15	8	12	19	5	117
	0.20	10	15	26	7	156
	0.30	16	23	39	11	234
	0.40	21	31	52	14	311
	0.50	26	39	65	18	389
	0.60	31	46	78	22	467
	0.70	37	54	91	25	545
	0.80	42	62	104	29	623
	0.90	47	70	117	32	701
	1.00	52	77	130	36	779

* The visibility ranges are based on Equation 1.

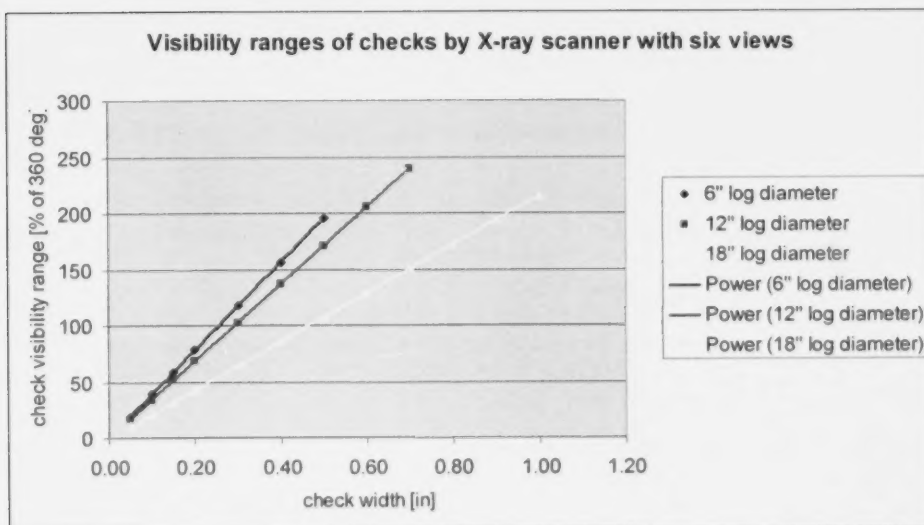


Figure 25. Visibility ranges of checks, for X-ray scanner with six views.

3.1.2 Check characterization

The results of this experiment show that when a check is visible, generally its position (i.e., the angular orientation) is determined with an error of $<1^\circ$, and the width is determined with error of 0.020 inches and a standard deviation of 0.10 inches. It is our belief that such accuracy is more than adequate for the purposes of optimizing log sorting and breakdown.

Executing the measurement of check depth is quite challenging and requires the use of sophisticated image processing algorithms such as those developed in this project. The accuracy with which the check depth can be estimated is given by Equation 2. Generally the error with which the check depth can be estimated increases linearly with the check depth, angle relative to the direction of X-rays, and average error in calculating the length of the X-ray passage from one side of the check to the other side, but the error increases nearly inversely with check width.

Equation 2 applies only to the visible checks that constrain the value of parameters in Equation 2 and thus limit the magnitude of the check depth error. Some measurements were made on the sample of beetle-killed logs at different positions along the log length (e.g., Figures 15, 16, and 17). Their accuracy was in agreement with Equation 2. The depth of these checks was approximately 3 inches and the width was about 0.2 inches; in most cases the estimated check depth was within 0.25 inches of the actual depth.

3.1.3 Limitations of check visibility and characterization

Checks could be detected and characterized robustly only in log cross-sections that had uniform or slowly varying density distribution. When a log cross-section included defects such as knots or other localized volumes of significantly different density, such as ice or wet parts of log surface, it made (automated) check detection and characterization very difficult or impossible.

3.2 Minimum technical requirements

The results of this experiment show that an X-ray scanner with as many views as technically feasible is the best choice. An X-ray scanner with six views was considered in this project because that is the largest number available in commercial systems. Appendix G includes information about an X-ray scanner with six views made by Bintec Oy, a collaborator on this project.

3.3 Using X-ray scanning systems for log sorting

One of the planned scenarios was to use the X-ray scanner to divert highly checked, low-value logs from being processed in the sawmill. However, the basic economics of handling such logs is as follows:

Delivered log cost	\$50/m ³
Whole log chipping cost	<u>\$12/m³</u>
Total cost	\$62/m ³
Value of chips	<u>\$28/m³</u>
Loss	\$34/m ³

The above does not include the costs of using the X-ray scanner. The preliminary simulations did show that the value recovery in the sawmill does improve with the use of an X-ray scanner, but not enough to cover the losses incurred from chipping low-value checked logs. Therefore, unless a higher revenue from severely checked logs is found, the obvious conclusion is to not bring these logs to the sawmill.

On the other hand, if X-ray scanning is used for identifying higher value logs in the sorting phase, such as peeler logs that would not otherwise be sorted, then scanning could make a positive contribution.

3.4 Increase in lumber value recovery and estimate of return on investment

The OPTITEK® sawmill simulation software was used to model optimal log sorting and breakdown in the scenarios considered in this project and to calculate the value of the output products, including sawdust and chips, for each of the sample logs. Figures 26 and 27 show these value recoveries for four scenarios: Current Mill Healthy logs (CMH), Current Mill Checked logs (CMC), Perfect Mill (PM) and X-ray mill Not Perfect (XNP) to facilitate the discussion. Related data are presented in Appendix H.

The data in Figure 26 (and Figure 27) have a unique form because (as discussed in Section 2.3.2.2) the sample logs within each diameter class are numbered (sorted) by the percentage drop in the value recovery between scenarios CMH and CMC. The value recovery data show the following trends:

- The recovery is highest in scenario CMH, lowest in scenario CMC and in scenario PM the recovery varies within the full range of the CMH and CMC scenarios.
- In scenario CMH, the recovery increases almost linearly with increasing log diameter from approximately 100 (\$/m³) to 120 (\$/m³).
- In scenario CMC, the recovery decreases within each diameter class with increasing severity of checking. The value loss is greatest for the smallest diameter logs (in the first diameter class) and it lessens with increasing log diameter.

Figure 27 shows the same data as in Figure 26 but only for logs in diameter class 1. Also shown is the scenario XNP. The value recoveries for scenario XNP were estimated on the basis of visual examination of the OPTITEK[®] sawmill simulation results (i.e., sawing patterns) for this scenario which (unfortunately) did not include the heuristic rules for connecting and extending the checks. Consequently, these results have understated the value recovery that could be realistically achieved in this scenario with the heuristic rules implemented. Trend lines fitted to the data show that on average, the impact of checking on value recovery could be reduced (mitigated) by approximately 50% in PM scenario and 25% in XNP scenario.

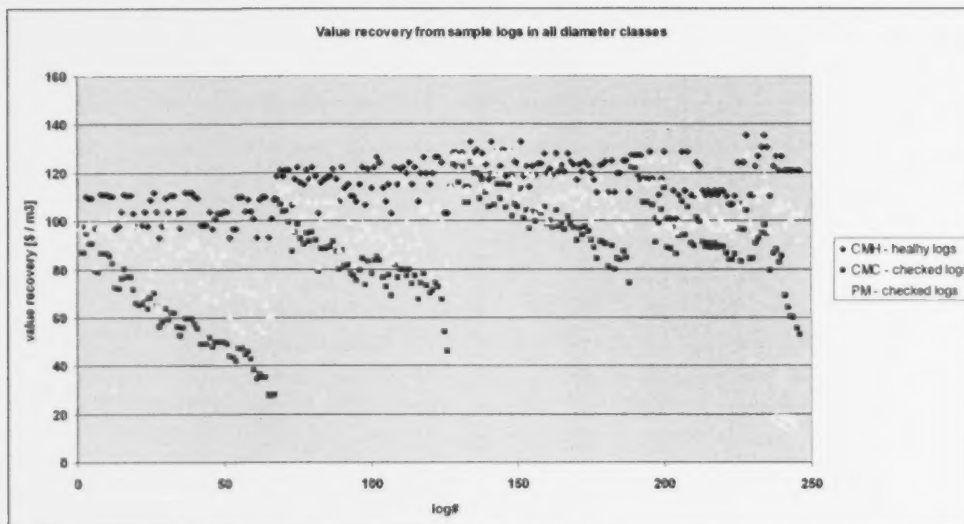


Figure 26. Value recoveries from sample logs in all diameter classes. See Appendix H for tables and data.

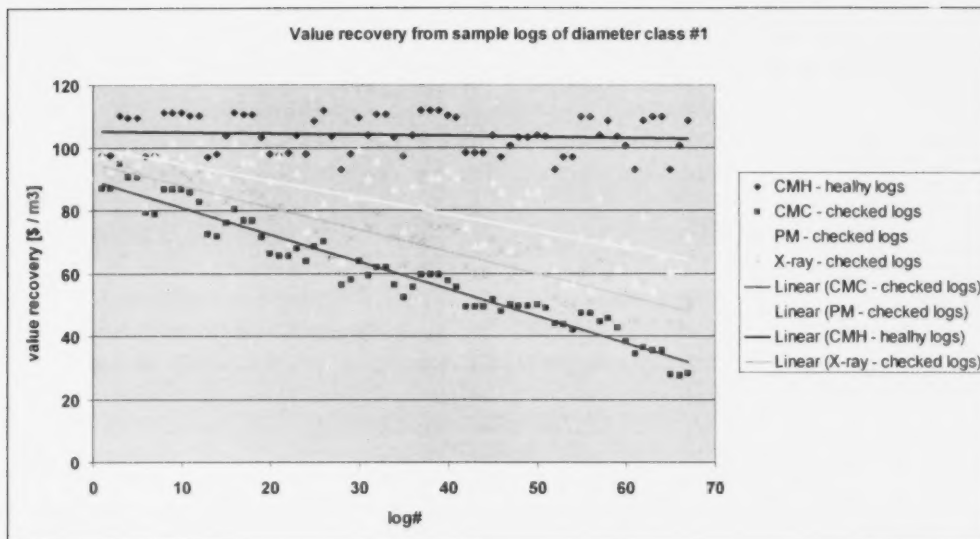


Figure 27. Value recoveries from sample logs in Diameter Class 1. See Appendix H for tables and data.

3.4.1 Incremental income

Return on investment was calculated as:

$$\text{Return on capital invested or incremental operating profit} \div \text{invested capital.}$$

In this case, the invested capital was \$9.7 million and the corporate tax rate of 33.1% was used. Returns were compiled on a yearly basis, consisting of 500 shifts, each consuming 1852 m³ of logs. The incremental operating profit was determined by subtracting the total revenue generated by a scenario using the X-ray scanning facility from the total revenue generated by the Current Mill scenario (Table 7).

Note that a positive incremental profit does not guarantee a profit for the sawmill. It does mean more net income, but that could be realized as a reduced operating loss.

The incremental profit, and the incremental returns on investment (Table 8), show that an X-ray scanner will increase net income but only if its check-detection capability is above certain thresholds (Table 9).

Table 7. Changes in incremental operating profit (not including capital cost of X-ray scanner).

Degree of checking in log supply	Mill scenario		Difference (\$/m ³)
	Current Mill (\$/m ³)	Perfect Mill X-ray (\$/m ³)	
Light	1.89	11.72	9.83
Medium	-5.56	7.94	13.50
Severe	-15.28	2.54	17.82

Table 8. Incremental return on investment for different levels of check detection capability of the X-ray scanner and degrees of checking in the log supply.

Check knowledge	Check capability (%)	Degree of checking in log supply		
		Light (%)	Medium (%)	Severe (%)
Perfect	100	34	54	84
Imperfect	75	18	35	56
Imperfect	50	2	12	27
Imperfect	25	-20	-12	-1
Current Mill technology	0	n/a	n/a	n/a

Table 9. Minimum check-detection capability for positive incremental return on investment.

Check-detection capability	Degree of checking in log supply		
	Light (%)	Medium (%)	Severe (%)
Threshold	48	38	26

The estimates of incremental profit and return on investment show two trends:

1. The value of having an X-ray scanner increases with the log supply's degree of checking.
2. As the degree of checking increases, a less capable X-ray scanner can return value.

The expected check capability of a commercial X-ray scanner is about 50%. A 75% capability is not expected due to the limits of X-ray scanning, software complexity, and the generally difficult nature of checks. At 50% capability, the X-ray scanner has only a 2% return on investment for a log supply with a light degree of checking, which would not justify investment. At a 12% return on investment for a log supply with a medium degree of checking, the investment becomes interesting. With an increase in check capability to even 60%, the return on investment would increase to about 22% for a log supply with medium checking.

The return on investment values for the severely checked log supply would be 12% higher than for the log supply with medium checking.

4 Conclusions

Use of an X-ray scanner with six views in a sawmill in the Interior of British Columbia has the potential to detect and characterize larger checks in beetle-affected logs accurately enough to optimize log sorting and breakdown. An X-ray scanner would enable a sawmill to substantially increase the value of its products when processing beetle-affected log supplies with medium and severe levels of checking. In some cases, the return on investment of an X-ray scanner could be as high as 27%.

The key outcomes of the study are summarized below:

1. An X-ray scanner with six views has the potential to detect and characterize larger checks in beetle-affected logs accurately enough to substantially increase value. To do so, the providers of the combined X-ray and laser scanning systems would have to develop software that detects and characterizes checks and optimizes log sorting and breakdown.
2. The economic return increases as the degree of checking in the log supply increases. For lightly checked logs, the return on investment is low because the opportunity to realize increased values is low. For log supplies with a medium or severe incidence of checks the X-ray scanner leads to a higher return on investment.

3. To realize a meaningful increase in value recovery and return on investment, it is essential that optimal sawing information obtained with the help of the X-ray scanner is somehow "attached" to each log as it progresses through the stages of processing in the sawmill.
4. The economic analysis indicates that an X-ray scanner must detect about 50% to 60% of the checks in order to realize a meaningful increase in value recovery and return on investment. This is about the level of detection expected from a commercial scanning system.
5. If pulp logs comprise a significant proportion of the log supply, any benefits of using an X-ray scanner at the sawmill may be negated. This scenario may change if the price of biomass increases or if high-value logs, such as peelers, could be identified.
6. The analysis of return on investment is based on an average sawmill cutting an assumed distribution of beetle-affected logs. If the installation of an X-ray scanner is contemplated, the simulation data would have to be calibrated to the sawmill to obtain more accurate projections.

5 Recommendations for Further Research

Our study has shown that an X-ray scanner could be used to detect and characterize checks in beetle-affected logs processed in sawmills in the Interior of British Columbia, and it has provided estimates of increases in value recovery and return on investment that would be facilitated by the scanner. The items proposed below would make these estimates more accurate and also lead to greater understanding of how this new technology could be most effectively used.

1. Validate the feasibility of using heuristic rules to connect and extend the checks into one continuous check, and of using triangulation to determine which side of the log has the check when one is visible in at least two views.
2. Use OPTITEK[®] simulations to quantify the value of Item 1.
3. Determine potential further increases in value recovery and return on investment when, in addition to checks, defects such as knots, rot, and other log characteristics (see Appendix G) are also detected by the X-ray scanner and are also used to optimize log sorting and breakdown.
4. Investigate approaches for determining how information about optimal sawing patterns could be "attached" to each log as it progresses through the sawmill.
5. Use the tools developed in this study to analyze the potential increases in value recovery and return on investment associated with using an X-ray scanner for log sorting. This would include modeling a log supply to include low-value and high-value logs.

6 Acknowledgements

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7 Contact

Jan Brdicko, Senior Research Scientist
FPInnovations-Forintek Division
Phone: 604-222-5660
Jan.Brdicko@fpinnovations.ca

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Appendix A. About OPTITEK®

OPTITEK® is a sophisticated sawmill simulation software application developed in 1989 at FPInnovations–Forintek Division. OPTITEK® has been periodically upgraded to accurately simulate log breakdown and lumber manufacturing in green sawmills of various layouts, including in the mill's commonly used machine centers. OPTITEK® can be used to determine changes in the recovery of lumber, chips, and sawdust due to potential changes in log characteristics (including knots and checks), sorting and bucking strategies, sawing patterns, product mix, prices, grade rules, type of equipment, and equipment accuracy.

To determine the volume of finished lumber and value recoveries, usually spreadsheet calculations are used to convert the green lumber (as determined by the OPTITEK® simulation) into the planer mill output in terms of the mix of lumber sizes and lengths with actual market grades and prices.

Base Case

In a typical OPTITEK® study a base case analysis is done first. By gathering data about the Current Mill layout, machinery, breakdown strategies, and products, as well as characteristics of the current log supply and lumber grade out-turns in the green and planer mills, the user can create an OPTITEK® model of the Current Mill and its operation. The log supply is usually represented by a “statistically valid” sample of logs. Defects in these logs may be measured in the log yard. The logs are then processed in the sawmill to capture their true shape data and record the green and finished lumber that is produced. The actual lumber production may then be compared that modelled by OPTITEK®. Any large differences between the actual and virtual lumber productions can be minimized by adjusting the model's parameters. This process is referred to as the validation of the base case sawmill model.

What-if Scenarios

After the base case analysis is completed, what-if scenarios can be performed. These could include examinations of log supply, sawmill machinery, and product mix. MPB-specific studies could include an increase in checked logs, defect-detection machinery, and different optimization patterns. The what-if scenarios could provide information for analyzing cost-benefits and determining return on investment.

Accuracy of Results of OPTITEK® Study

During the past 15 years OPTITEK® has been used in hundreds of sawmill studies in which healthy, check-free logs were considered and the accuracy of the simulation results was thoroughly verified. In 2007 OPTITEK® was upgraded to also simulate the operation of sawmills processing checked logs. This upgrade to OPTITEK® included:

- extensive changes to the software for manipulating the models of logs containing checks and for sawing them (in the virtual sense) into boards,
- determining whether the checks intersect the boards as splits or shake, and
- adding the grading rules that affect the boards with these defects.

The accuracy of the simulation results has been verified in the course of several simpler projects and found satisfactory.

Appendix B. Shape and check data of sample logs

Table B-1. Shape and check data for sample logs in Diameter Class 1.

Parent Log #	Log #	AvgDse	AvgDle	AvgSwp	AvgTap	AvgLgt	AvgVol	# of checks	avg. length	avg. depth	Total Check Area	angle rel to parent
		(in)	(in)	(in/8ft)	(in/8ft)	(ft)	(m3)		(in)	(in)	(in ²)	(deg)
1	1	5.4	6.73	0.26	0.64	16.67	0.10	1	70	2.77	194	0
1	2	5.4	6.73	0.26	0.64	16.67	0.10	1	70	2.77	194	90
1	3	5.4	6.73	0.26	0.64	16.67	0.10	1	70	2.77	194	180
1	4	5.4	6.73	0.26	0.64	16.67	0.10	1	70	2.77	194	270
2	5	6.15	7.42	0.52	0.61	16.67	0.13	2	55	2.62	144	0
2	6	6.15	7.42	0.52	0.61	16.67	0.13	2	55	2.62	144	90
2	7	6.15	7.42	0.52	0.61	16.67	0.13	2	55	2.62	144	180
2	8	6.15	7.42	0.52	0.61	16.67	0.13	2	55	2.62	144	270
3	9	6.07	7.07	0.55	0.49	16.33	0.11	1	176	3.58	629	0
3	10	6.07	7.07	0.55	0.49	16.33	0.11	1	176	3.58	629	90
3	11	6.07	7.07	0.55	0.49	16.33	0.11	1	176	3.58	629	270
4	12	4.72	5.38	0.32	0.31	16.67	0.07	1	89	1.78	159	0
4	13	4.72	5.38	0.32	0.31	16.67	0.07	1	89	1.78	159	90
4	14	4.72	5.38	0.32	0.31	16.67	0.07	1	89	1.78	159	180
4	15	4.72	5.38	0.32	0.31	16.67	0.07	1	89	1.78	159	270
5	16	5.87	7.24	0.29	0.66	16.67	0.11	1	74	2.43	180	0
5	17	5.87	7.24	0.29	0.66	16.67	0.11	1	74	2.43	180	90
5	18	5.87	7.24	0.29	0.66	16.67	0.11	1	74	2.43	180	180
5	19	5.87	7.24	0.29	0.66	16.67	0.11	1	74	2.43	180	270
6	20	6.74	7.69	0.29	0.45	16.67	0.14	2	72	1.87	135	0
6	21	6.74	7.69	0.29	0.45	16.67	0.14	2	72	1.87	135	90
6	22	6.74	7.69	0.29	0.45	16.67	0.14	2	72	1.87	135	180
6	23	6.74	7.69	0.29	0.45	16.67	0.14	2	72	1.87	135	270
7	24	5.26	7.02	0.66	0.84	16.67	0.11	4	88	1.53	134	0
7	25	5.26	7.02	0.66	0.84	16.67	0.11	4	88	1.53	134	90
7	26	5.26	7.02	0.66	0.84	16.67	0.11	4	88	1.53	134	180
7	27	5.26	7.02	0.66	0.84	16.67	0.11	4	88	1.53	134	270
8	28	6.61	7.9	1.17	0.62	16.67	0.13	2	98	2.13	207	0
8	29	6.61	7.9	1.17	0.62	16.67	0.13	2	98	2.13	207	180
9	30	5.48	6.95	0.66	0.71	16.67	0.10	1	86	2.25	193	0
9	31	5.48	6.95	0.66	0.71	16.67	0.10	1	86	2.25	193	90
9	32	5.48	6.95	0.66	0.71	16.67	0.10	1	86	2.25	193	180
9	33	5.48	6.95	0.66	0.71	16.67	0.10	1	86	2.25	193	270
10	34	5.02	6.29	0.7	0.61	16.67	0.08	2	76	2.03	154	0
10	35	5.02	6.29	0.7	0.61	16.67	0.08	2	76	2.03	154	90
10	36	5.02	6.29	0.7	0.61	16.67	0.08	2	76	2.03	154	180
10	37	5.02	6.29	0.7	0.61	16.67	0.08	2	76	2.03	154	270
11	38	4.46	5.45	0.43	0.47	16.67	0.07	2	109	2.36	256	0
11	39	4.46	5.45	0.43	0.47	16.67	0.07	2	109	2.36	256	90
11	40	4.46	5.45	0.43	0.47	16.67	0.07	2	109	2.36	256	180
12	41	5.07	5.89	0.39	0.4	16.33	0.08	1	158	2.05	324	0
12	42	5.07	5.89	0.39	0.4	16.33	0.08	1	158	2.05	324	90
12	43	5.07	5.89	0.39	0.4	16.33	0.08	1	158	2.05	324	180
12	44	5.07	5.89	0.39	0.4	16.33	0.08	1	158	2.05	324	270
13	45	5.04	5.97	0.41	0.44	16.67	0.08	2	107	2.11	225	0
13	46	5.04	5.97	0.41	0.44	16.67	0.08	2	107	2.11	225	90
13	47	5.04	5.97	0.41	0.44	16.67	0.08	2	107	2.11	225	180
13	48	5.04	5.97	0.41	0.44	16.67	0.08	2	107	2.11	225	270
14	49	5.66	7.8	0.28	1.03	16.67	0.13	1	93	1.72	160	0
14	50	5.66	7.8	0.28	1.03	16.67	0.13	1	93	1.72	160	90
14	51	5.66	7.8	0.28	1.03	16.67	0.13	1	93	1.72	160	180
14	52	5.66	7.8	0.28	1.03	16.67	0.13	1	93	1.72	160	270
15	53	4.77	6.7	0.64	0.93	16.67	0.08	1	172	2.25	387	0
15	54	4.77	6.7	0.64	0.93	16.67	0.08	1	172	2.25	387	90
15	55	4.77	6.7	0.64	0.93	16.67	0.08	1	172	2.25	387	180
15	56	4.77	6.7	0.64	0.93	16.67	0.08	1	172	2.25	387	270
16	57	5.76	6.88	0.69	0.54	16.67	0.11	1	136	1.88	256	0
16	58	5.76	6.88	0.69	0.54	16.67	0.11	1	136	1.88	256	90
16	59	5.76	6.88	0.69	0.54	16.67	0.11	1	136	1.88	256	180
16	60	5.76	6.88	0.69	0.54	16.67	0.11	1	136	1.88	256	270
17	61	5.8	6.6	0.41	0.38	16.67	0.10	2	76	1.76	133	0
17	62	5.8	6.6	0.41	0.38	16.67	0.10	2	76	1.76	133	90
17	63	5.8	6.6	0.41	0.38	16.67	0.10	2	76	1.76	133	180
17	64	5.8	6.6	0.41	0.38	16.67	0.10	2	76	1.76	133	270
18	65	5.14	6.39	0.48	0.6	16.67	0.09	2	70	1.92	135	0
18	66	5.14	6.39	0.48	0.6	16.67	0.09	2	70	1.92	135	90
18	67	5.14	6.39	0.48	0.6	16.67	0.09	2	70	1.92	135	180

Table B-2. Shape and check data for sample logs in Diameter Class 2.

Parent Log #	Log #	AvgDse (in)	AvgDle (in)	AvgSwp (in/8ft)	AvgTap (in/8ft)	AvgLgt (ft)	AvgVol (m3)	# of checks	avg. length (in)	avg. depth (in)	Total Check Area (in^2)	angle rel to parent (deg)
19	68	7.18	8.39	0.14	0.58	16.67	0.15	1	168	1.94	326	0
19	69	7.18	8.39	0.14	0.58	16.67	0.15	1	168	1.94	326	90
19	70	7.18	8.39	0.14	0.58	16.67	0.15	1	168	1.94	326	180
19	71	7.18	8.39	0.14	0.58	16.67	0.15	1	168	1.94	326	270
20	72	8.31	9.89	0.34	0.76	16.67	0.22	1	56	1.87	105	0
20	73	8.31	9.89	0.34	0.76	16.67	0.22	1	56	1.87	105	90
20	74	8.31	9.89	0.34	0.76	16.67	0.22	1	56	1.87	105	180
20	75	8.31	9.89	0.34	0.76	16.67	0.22	1	56	1.87	105	270
21	76	5.75	7.7	0.45	0.94	16.67	0.14	2	89	2.34	207	0
21	77	5.75	7.7	0.45	0.94	16.67	0.14	2	89	2.34	207	90
21	78	5.75	7.7	0.45	0.94	16.67	0.14	2	89	2.34	207	180
21	79	5.75	7.7	0.45	0.94	16.67	0.14	2	89	2.34	207	270
22	80	6.44	7.77	0.31	0.65	16.33	0.14	1	84	1.96	164	0
22	81	6.44	7.77	0.31	0.65	16.33	0.14	1	84	1.96	164	270
23	82	8.87	10.25	1.11	0.66	16.67	0.25	2	71	3.32	236	0
23	83	8.87	10.25	1.11	0.66	16.67	0.25	2	71	3.32	236	90
23	84	8.87	10.25	1.11	0.66	16.67	0.25	2	71	3.32	236	180
23	85	8.87	10.25	1.11	0.66	16.67	0.25	2	71	3.32	236	270
24	86	7.77	9.29	0.41	0.73	16.67	0.20	1	139	2.59	360	0
24	87	7.77	9.29	0.41	0.73	16.67	0.20	1	139	2.59	360	90
24	88	7.77	9.29	0.41	0.73	16.67	0.20	1	139	2.59	360	180
24	89	7.77	9.29	0.41	0.73	16.67	0.20	1	139	2.59	360	270
25	90	7.8	9.98	0.37	1.07	16.33	0.20	1	133	2.03	270	0
25	91	7.8	9.98	0.37	1.07	16.33	0.20	1	133	2.03	270	90
25	92	7.8	9.98	0.37	1.07	16.33	0.20	1	133	2.03	270	180
25	93	7.8	9.98	0.37	1.07	16.33	0.20	1	133	2.03	270	270
26	94	9.36	10.7	0.54	0.64	16.67	0.27	3	75	2.16	162	0
26	95	9.36	10.7	0.54	0.64	16.67	0.27	3	75	2.16	162	90
26	96	9.36	10.7	0.54	0.64	16.67	0.27	3	75	2.16	162	180
26	97	9.36	10.7	0.54	0.64	16.67	0.27	3	75	2.16	162	270
27	98	7.68	9.1	0.89	0.68	16.67	0.19	1	180	2.49	449	0
27	99	7.68	9.1	0.89	0.68	16.67	0.19	1	180	2.49	449	90
27	100	7.68	9.1	0.89	0.68	16.67	0.19	1	180	2.49	449	180
27	101	7.68	9.1	0.89	0.68	16.67	0.19	1	180	2.49	449	270
28	102	6.89	8.82	0.19	0.93	16.67	0.17	2	74	2.73	202	180
29	103	7.85	8.93	0.29	0.53	16.33	0.18	3	106	1.30	138	90
29	104	7.85	8.93	0.29	0.53	16.33	0.18	3	106	1.30	138	180
29	105	7.85	8.93	0.29	0.53	16.33	0.18	3	106	1.30	138	270
30	106	7.33	9.24	0.73	0.92	16.67	0.18	1	200	2.00	400	0
30	107	7.33	9.24	0.73	0.92	16.67	0.18	1	200	2.00	400	90
31	108	7.31	8.39	0.41	0.52	16.67	0.16	1	112	1.97	221	0
31	109	7.31	8.39	0.41	0.52	16.67	0.16	1	112	1.97	221	90
31	110	7.31	8.39	0.41	0.52	16.67	0.16	1	112	1.97	221	180
31	111	7.31	8.39	0.41	0.52	16.67	0.16	1	112	1.97	221	270
32	112	7.35	8.45	0.18	0.52	17	0.17	2	42	2.28	96	0
32	113	7.35	8.45	0.18	0.52	17	0.17	2	42	2.28	96	90
32	114	7.35	8.45	0.18	0.52	17	0.17	2	42	2.28	96	180
32	115	7.35	8.45	0.18	0.52	17	0.17	2	42	2.28	96	270
33	116	8.61	10.28	0.4	0.8	16.67	0.25	2	107	2.70	288	0
33	117	8.61	10.28	0.4	0.8	16.67	0.25	2	107	2.70	288	90
33	118	8.61	10.28	0.4	0.8	16.67	0.25	2	107	2.70	288	270
34	119	7.42	8.24	0.35	0.39	16.67	0.16	2	100	2.47	247	0
34	120	7.42	8.24	0.35	0.39	16.67	0.16	2	100	2.47	247	90
34	121	7.42	8.24	0.35	0.39	16.67	0.16	2	100	2.47	247	270
35	122	6.55	7.76	0.37	0.58	16.67	0.14	1	120	2.14	257	0
35	123	6.55	7.76	0.37	0.58	16.67	0.14	1	120	2.14	257	90
36	124	8.19	9.89	0.46	0.82	16.67	0.20	2	95	2.70	255	0
36	125	8.19	9.89	0.46	0.82	16.67	0.20	2	95	2.70	255	90
36	126	8.19	9.89	0.46	0.82	16.67	0.20	2	95	2.70	255	270

Table B-3. Shape and check data for sample logs in Diameter Class 3.

Parent Log #	Log #	AvgDse	AvgDle	AvgSwp	AvgTap	AvgLgt	AvgVol	# of checks	avg. length	avg. depth	Total Check Area	angle rel to parent
		(in)	(in)	(in/8ft)	(in/8ft)	(ft)	(m3)		(in)	(in)	(in ²)	(deg)
37	127	9.66	11.38	0.32	0.82	16.67	0.29	1	144	3.40	490	0
37	128	9.66	11.38	0.32	0.82	16.67	0.29	1	144	3.40	490	180
37	129	9.66	11.38	0.32	0.82	16.67	0.29	1	144	3.40	490	270
38	130	10.55	12.16	0.55	0.77	16.67	0.32	1	72	2.24	161	0
38	131	10.55	12.16	0.55	0.77	16.67	0.32	1	72	2.24	161	90
38	132	10.55	12.16	0.55	0.77	16.67	0.32	1	72	2.24	161	180
39	133	10.68	12.26	0.38	0.76	16.67	0.34	1	65	4.35	283	0
39	134	10.68	12.26	0.38	0.76	16.67	0.34	1	65	4.35	283	90
39	135	10.68	12.26	0.38	0.76	16.67	0.34	1	65	4.35	283	180
40	136	9.5	11.13	0.69	0.78	16.67	0.28	2	98	1.77	173	0
40	137	9.5	11.13	0.69	0.78	16.67	0.28	2	98	1.77	173	90
40	138	9.5	11.13	0.69	0.78	16.67	0.28	2	98	1.77	173	180
41	139	11.15	12.8	0.52	0.79	16.67	0.38	1	120	2.25	270	0
41	140	11.15	12.8	0.52	0.79	16.67	0.38	1	120	2.25	270	90
41	141	11.15	12.8	0.52	0.79	16.67	0.38	1	120	2.25	270	180
42	142	12.19	13.82	0.21	0.78	16.67	0.44	1	83	1.53	127	0
42	143	12.19	13.82	0.21	0.78	16.67	0.44	1	83	1.53	127	90
42	144	12.19	13.82	0.21	0.78	16.67	0.44	1	83	1.53	127	180
42	145	12.19	13.82	0.21	0.78	16.67	0.44	1	83	1.53	127	270
43	146	9.71	11.76	0.63	0.98	16.67	0.31	1	68	1.85	126	0
43	147	9.71	11.76	0.63	0.98	16.67	0.31	1	68	1.85	126	90
43	148	9.71	11.76	0.63	0.98	16.67	0.31	1	68	1.85	126	180
43	149	9.71	11.76	0.63	0.98	16.67	0.31	1	68	1.85	126	270
44	150	10.1	11.94	0.71	0.88	16.67	0.33	1	95	2.54	241	0
44	151	10.1	11.94	0.71	0.88	16.67	0.33	1	95	2.54	241	90
44	152	10.1	11.94	0.71	0.88	16.67	0.33	1	95	2.54	241	180
44	153	10.1	11.94	0.71	0.88	16.67	0.33	1	95	2.54	241	270
45	154	9.94	11.6	0.43	0.81	16.33	0.30	1	196	2.84	556	0
45	155	9.94	11.6	0.43	0.81	16.33	0.30	1	196	2.84	556	90
45	156	9.94	11.6	0.43	0.81	16.33	0.30	1	196	2.84	556	180
45	157	9.94	11.6	0.43	0.81	16.33	0.30	1	196	2.84	556	270
46	158	10.13	12.14	0.23	0.97	16.67	0.32	1	200	4.47	895	0
46	159	10.13	12.14	0.23	0.97	16.67	0.32	1	200	4.47	895	90
46	160	10.13	12.14	0.23	0.97	16.67	0.32	1	200	4.47	895	180
46	161	10.13	12.14	0.23	0.97	16.67	0.32	1	200	4.47	895	270
47	162	11.73	13.46	0.38	0.83	16.67	0.42	2	96	2.22	213	0
47	163	11.73	13.46	0.38	0.83	16.67	0.42	2	96	2.22	213	90
47	164	11.73	13.46	0.38	0.83	16.67	0.42	2	96	2.22	213	180
47	165	11.73	13.46	0.38	0.83	16.67	0.42	2	96	2.22	213	270
48	166	11.12	13.23	0.27	1.01	16.67	0.39	1	49	2.83	139	0
48	167	11.12	13.23	0.27	1.01	16.67	0.39	1	49	2.83	139	90
48	168	11.12	13.23	0.27	1.01	16.67	0.39	1	49	2.83	139	180
48	169	11.12	13.23	0.27	1.01	16.67	0.39	1	49	2.83	139	270
49	170	9.6	10.94	0.37	0.64	16.67	0.28	2	95	1.71	162	0
49	171	9.6	10.94	0.37	0.64	16.67	0.28	2	95	1.71	162	90
49	172	9.6	10.94	0.37	0.64	16.67	0.28	2	95	1.71	162	180
50	173	10.17	11.72	0.29	0.74	16.67	0.31	3	58	1.48	86	0
50	174	10.17	11.72	0.29	0.74	16.67	0.31	3	58	1.48	86	90
50	175	10.17	11.72	0.29	0.74	16.67	0.31	3	58	1.48	86	180
51	176	11.28	14.36	0.83	1.48	16.67	0.40	3	97	1.48	143	0
51	177	11.28	14.36	0.83	1.48	16.67	0.40	3	97	1.48	143	90
51	178	11.28	14.36	0.83	1.48	16.67	0.40	3	97	1.48	143	180
52	179	11.28	14.03	0.38	1.29	17	0.41	2	76	2.82	213	0
52	180	11.28	14.03	0.38	1.29	17	0.41	2	76	2.82	213	90
52	181	11.28	14.03	0.38	1.29	17	0.41	2	76	2.82	213	180
52	182	11.28	14.03	0.38	1.29	17	0.41	2	76	2.82	213	270
53	183	11.04	12.75	0.46	0.82	16.67	0.37	1	115	1.75	201	0
53	184	11.04	12.75	0.46	0.82	16.67	0.37	1	115	1.75	201	90
54	185	12.36	14.96	0.33	1.32	15.67	0.45	2	146	3.73	546	0
54	186	12.36	14.96	0.33	1.32	15.67	0.45	2	146	3.73	546	90
54	187	12.36	14.96	0.33	1.32	15.67	0.45	2	146	3.73	546	180
54	188	12.36	14.96	0.33	1.32	15.67	0.45	2	146	3.73	546	270

Table B-4. Shape and check data for sample logs in Diameter Class 4.

Parent Log #	Log #	AvgDse	AvgDie	AvgSwp	AvgTap	AvgLgt	AvgVcl	# of checks	avg. length	avg. depth	Total Check Area	angle rel to parent
		(in)	(in)	(in/8ft)	(in/8ft)	(ft)	(m3)		(in)	(in)	(in^2)	(deg)
55	189	9.95	10.91	0.33	0.52	14.67	0.25	1	61	1.84	112	0
55	190	9.95	10.91	0.33	0.52	14.67	0.25	1	61	1.84	112	90
55	191	9.95	10.91	0.33	0.52	14.67	0.25	1	61	1.84	112	180
55	192	9.95	10.91	0.33	0.52	14.67	0.25	1	61	1.84	112	270
57	193	13.05	15.34	0.62	1.17	15.67	0.50	2	119	3.22	383	90
57	194	13.05	15.34	0.62	1.17	15.67	0.50	2	119	3.22	383	180
57	195	13.05	15.34	0.62	1.17	15.67	0.50	2	119	3.22	383	270
58	196	13.12	15.03	0.29	0.92	16.67	0.53	1	162	3.43	556	0
58	197	13.12	15.03	0.29	0.92	16.67	0.53	1	162	3.43	556	90
58	198	13.12	15.03	0.29	0.92	16.67	0.53	1	162	3.43	556	270
59	199	12.22	14.55	0.33	1.1	17	0.47	2	188	3.51	660	0
59	200	12.22	14.55	0.33	1.1	17	0.47	2	188	3.51	660	90
59	201	12.22	14.55	0.33	1.1	17	0.47	2	188	3.51	660	180
59	202	12.22	14.55	0.33	1.1	17	0.47	2	188	3.51	660	270
60	203	10.75	14.37	0.72	1.7	17	0.44	2	80	2.45	196	0
60	204	10.75	14.37	0.72	1.7	17	0.44	2	80	2.45	196	90
60	205	10.75	14.37	0.72	1.7	17	0.44	2	80	2.45	196	180
60	206	10.75	14.37	0.72	1.7	17	0.44	2	80	2.45	196	270
61	207	13.34	14.57	0.48	0.73	13.33	0.41	2	99	4.28	421	0
61	208	13.34	14.57	0.48	0.73	13.33	0.41	2	99	4.28	421	90
61	209	13.34	14.57	0.48	0.73	13.33	0.41	2	99	4.28	421	270
62	210	11.89	14.99	0.66	2.4	10.33	0.33	3	57	2.37	136	0
62	211	11.89	14.99	0.66	2.4	10.33	0.33	3	57	2.37	136	90
62	212	11.89	14.99	0.66	2.4	10.33	0.33	3	57	2.37	136	180
62	213	11.89	14.99	0.66	2.4	10.33	0.33	3	57	2.37	136	270
63	214	12.19	13.21	1.19	0.68	12	0.31	1	94	2.36	222	0
63	215	12.19	13.21	1.19	0.68	12	0.31	1	94	2.36	222	90
63	216	12.19	13.21	1.19	0.68	12	0.31	1	94	2.36	222	180
63	217	12.19	13.21	1.19	0.68	12	0.31	1	94	2.36	222	270
64	218	12.61	13.96	0.22	0.65	16.67	0.46	3	86	2.60	225	180
64	219	12.61	13.96	0.22	0.65	16.67	0.46	3	86	2.60	225	270
65	220	11.45	13.4	0.63	1.09	14.33	0.38	1	164	3.51	576	0
65	221	11.45	13.4	0.63	1.09	14.33	0.38	1	164	3.51	576	180
66	222	12.97	15.07	1.44	1.1	15.33	0.46	1	136	3.79	516	0
66	223	12.97	15.07	1.44	1.1	15.33	0.46	1	136	3.79	516	90
66	224	12.97	15.07	1.44	1.1	15.33	0.46	1	136	3.79	516	180
66	225	12.97	15.07	1.44	1.1	15.33	0.46	1	136	3.79	516	270
67	226	12.56	14.3	0.34	1.35	10.33	0.30	2	82	2.38	197	0
67	227	12.56	14.3	0.34	1.35	10.33	0.30	2	82	2.38	197	90
67	228	12.56	14.3	0.34	1.35	10.33	0.30	2	82	2.38	197	180
67	229	12.56	14.3	0.34	1.35	10.33	0.30	2	82	2.38	197	270
68	230	11.9	13.9	0.58	1.17	13.67	0.39	1	55	2.29	126	0
68	231	11.9	13.9	0.58	1.17	13.67	0.39	1	55	2.29	126	90
68	232	11.9	13.9	0.58	1.17	13.67	0.39	1	55	2.29	126	180
68	233	11.9	13.9	0.58	1.17	13.67	0.39	1	55	2.29	126	270
69	234	12	13.95	0.18	0.94	16.67	0.44	3	72	2.84	206	0
69	235	12	13.95	0.18	0.94	16.67	0.44	3	72	2.84	206	90
69	236	12	13.95	0.18	0.94	16.67	0.44	3	72	2.84	206	270
70	237	12.33	14.63	0.45	1.17	15.67	0.44	2	94	4.39	413	0
70	238	12.33	14.63	0.45	1.17	15.67	0.44	2	94	4.39	413	90
70	239	12.33	14.63	0.45	1.17	15.67	0.44	2	94	4.39	413	180
71	240	13.79	15.41	0.3	0.91	14.33	0.48	4	93	2.93	273	90
71	241	13.79	15.41	0.3	0.91	14.33	0.48	4	93	2.93	273	180
71	242	13.79	15.41	0.3	0.91	14.33	0.48	4	93	2.93	273	270
72	243	11.31	14.39	0.66	1.72	14.33	0.40	1	172	2.62	451	0
72	244	11.31	14.39	0.66	1.72	14.33	0.40	1	172	2.62	451	90
72	245	11.31	14.39	0.66	1.72	14.33	0.40	1	172	2.62	451	180
72	246	11.31	14.39	0.66	1.72	14.33	0.40	1	172	2.62	451	270

Appendix C. OPTITEK[®] Sawmill models

OPTITEK[®] sawmill models

Two unique OPTITEK[®] sawmill models were built: a “Current” Mill and a “Perfect” Mill. To reduce the study’s complexity it was decided not to include positioning and machining inaccuracies in the models.

Building the model of the Current Mill included developing a sawmill input file that describes the operation of the sawmill by mimicking how logs are rotated, and how cants, flitches, and boards are positioned and sawn into lumber.

Sawmill input file

- Each of the two identical production lines was simulated to represent: a Comact DDM6 canter (6-inch maximum cant size; conical 8-knife chipping heads, left and right circular quad saws with up to four sideboards; single arbour vertical gang, eight saws; top and bottom profiling heads for 4 inches off a 6-inch cant) and
- a Comact DDM 500 vertical, single-arbour curve sawing machine.

Diameter-dependent selection of five sawing patterns (Figures C-1 and C-2), optimized sweep-dependent log rotation (Figure C-3), and optimized log positioning within feasible sets of alignments and offsets (Figure C-4) were the components in optimizing log breakdown.

Optimal log position in the horizontal plane was simulated with a log alignment range of $(-0.5^\circ, 0.5^\circ)$ and an offset range of $(-1.5, 1.5)$ inches (Figure C-4).

In the vertical plane natural curve sawing was simulated as the modeled Comact DDM 500 machines mechanically follow external log geometry, i.e., there is no limit to the number of curves. A minimum curvature radius of 740 inches was used. It can curve-saw an 8-foot log with a sweep of 1.558 inch.

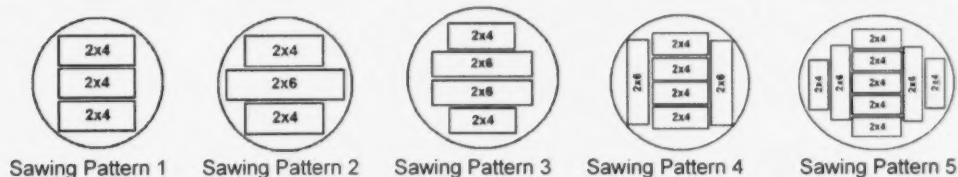


Figure C-1. Diagrams of the five sawing patterns. Asymmetric patterns are possible.

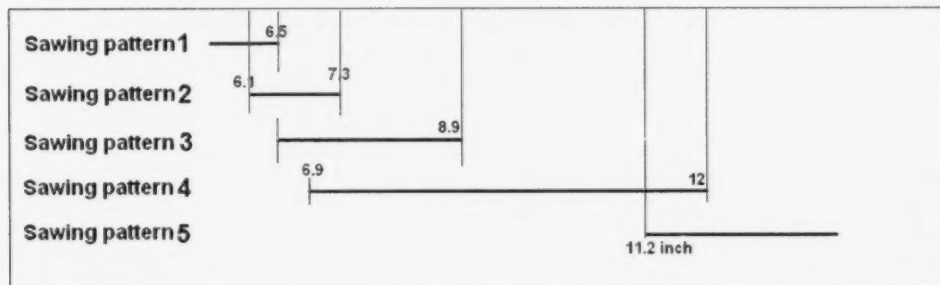


Figure C-2. Sawing patterns, and diameter ranges within which the patterns are used. Diameter is measured 2 inches from the small end.

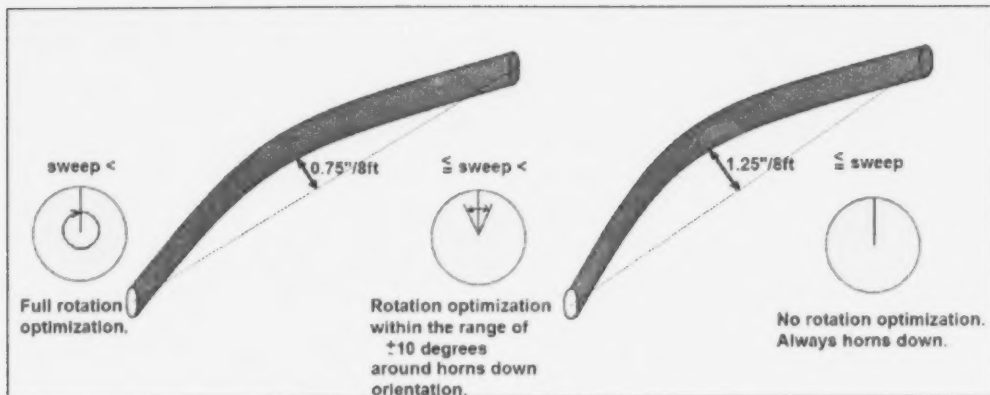


Figure C-3. Optimized sweep-dependent log rotation.

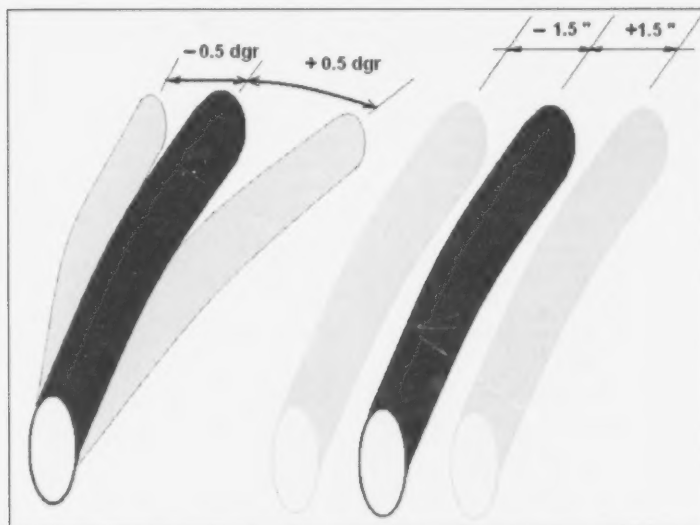


Figure C-4. Log alignment and offset ranges of the simulation.

Edger optimization

Figure C-5 describes how the operation of optimized edging is simulated. The optimized edging solution is selected from a reasonable set of solutions. Depending on the size of the boards, maximum three-piece solutions, board alignment, and offset are considered in the simulation. Six-inch wide pieces of center cant can be edged back if needed.

Trimmer optimization

Depending on board length, reasonable subsets of end product placements and lengths from Figure C-6 are selected to create feasible solutions for trimming optimization. The location of zero saw can be within the range of 4 ft from the board end by 6-inch increments.

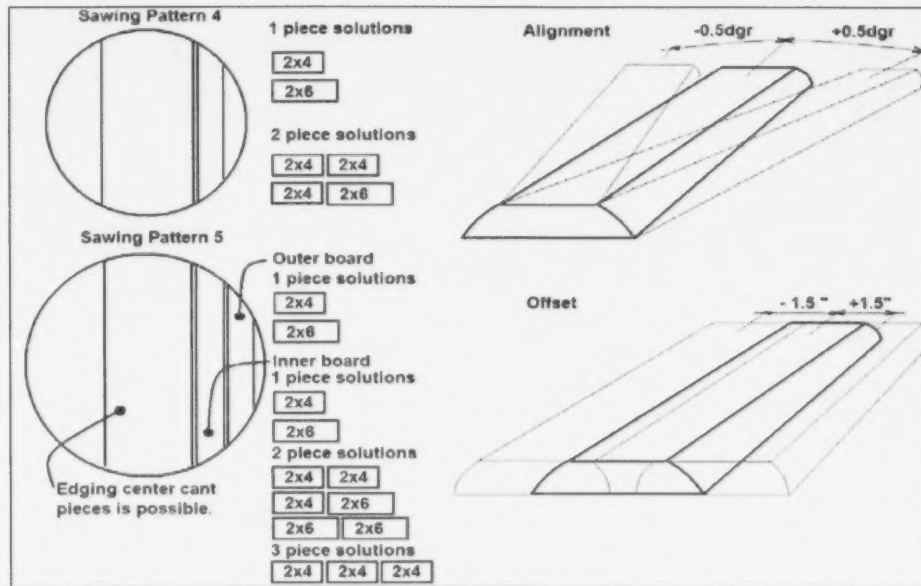


Figure C-5. Simulation of optimized edging.

		2	4	6	8	10	12	14	16
Extreme right lumb.position									
Extreme left lumb.position		2	4	6	8	10	12	14	16
Saw blade locations relative to Ref.lne									
Left Right									
0.5	98.685								
0.5	123.185								
0.5	147.685								
0.5	172.185								
0.5	196.685								
24.5	122.685								
24.5	147.185								
24.5	171.685								
24.5	196.185								

Figure C-6. Trimmer saw locations relative to moving fence (reference line). Moving fence parameters: step, [interval] = 6" [-24", 0]. Blade locations measured in inches; lumber position in feet.

Appendix D. Potential methods of deploying a scanner for X-raying logs in a sawmill

A few scenarios for deploying X-rays in a Current Mill are presented here. First the basic economics of a Current Mill are presented, followed by the same for X-ray deployments in that sawmill.

Current Mill Operation

Figure D-1, a schematic drawing of the Current Mill, shows only the major parameters required for comparison with the X-ray sawmill scenarios considered in this project. Logs, described by the delivered cost (\$/m³) and the volume consumed (m³/shift), are the only input. The logs may be free of checks, or checked at different levels of severity. A small fraction of the input log volume may end up as reject logs which, for simplicity, are assumed to be chipped in a whole log chipper separate from sawmill. The technology is typical of that used by sawmills in British Columbia's Interior region, i.e., using a primary log breakdown system with Double Length Infeed (DLI). Laser scanners optimize log turning and breakdown. The Current Mill is assumed to have no technologies to detect checks and no ability to use this knowledge to minimize the effects of checks by optimizing breakdown. The sawmill revenue (\$/shift) includes the value of finished lumber, pulp chips, sawdust, and hog fuel.

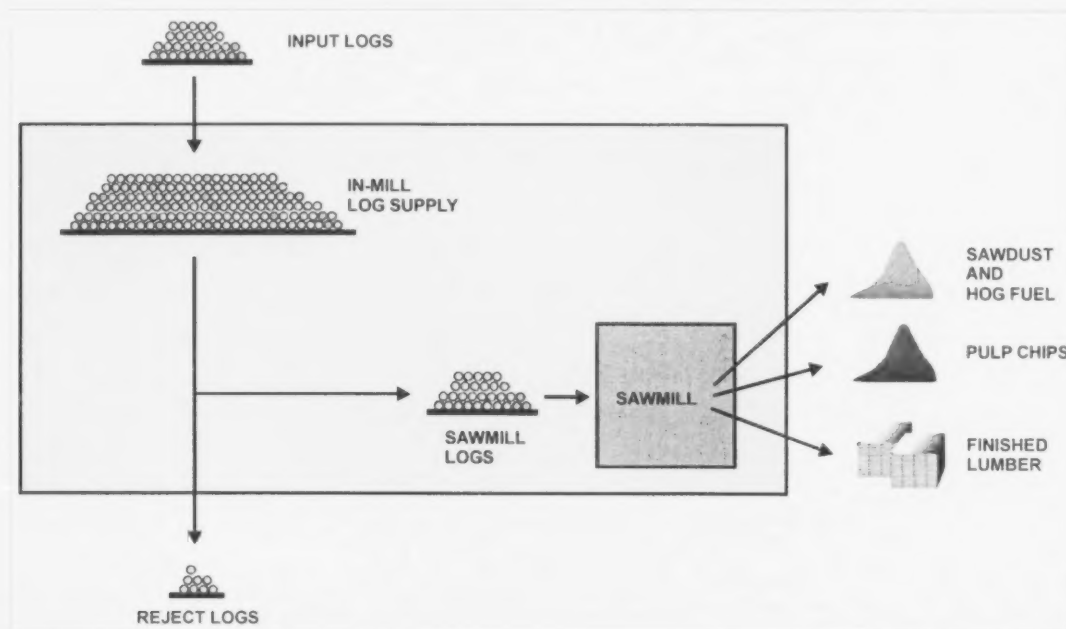


Figure D-1 . Operation of Current Mill.

The Current Mill scenario has no log-sorting facility and all input logs (except the reject logs) are processed in the sawmill.

Optimal log breakdown is based only on the log shape. The costs of the Current Mill that are relevant to making comparisons with a log-sorting mill are:

- Input logs
- Other

The revenues of the Current Mill that are relevant for making comparisons with a log-sorting mill are:

- Reject logs
- Sawdust and hog fuel
- Pulp chips
- Finished lumber
- Other

Mill Operation with Separate X-ray Facility for Scanning Logs

In this scenario, a complete log-sorting facility in the log yard operates independently of the sawmill (Figure D-2).

Figure D-2 shows the same sawmill as in Figure D-1 except that it now includes an X-ray log-sorting facility. Input logs are conveyed through a laser and X-ray scanners that detect and characterize checks and an optimal sawing pattern is produced. The sawing pattern's calculated value facilitates sorting logs into sawmill logs, pulp logs, and logs for other uses. Depending on the design of the log-sorting facility, the optimal sawing pattern information may be "attached" to each log for the use in the sawmill. As in the Current Mill scenario, the reject logs are chipped in a whole log chipper separate from the sawmill.

The incremental (i.e., additional) costs of a log-sorting sawmill that are relevant for making comparisons to the Current Mill are:

- Additional input logs
- Operational costs of log sorting facility (staff, maintenance, utilities, etc.)
- Depreciation
- Other

The incremental (i.e., additional positive or negative) revenues of a log-sorting sawmill that are relevant for making comparisons to the Current Mill are:

- Additional reject logs
- Pulp logs
- Peeler logs
- Other uses of logs
- Additional sawdust and hog fuel
- Additional pulp chips
- Additional finished lumber (volume and value)
- Other

Mill Operation with X-ray Log Scanner Deployed in the sawmill

A schematic of the front-end of a Current Mill that uses two log lines is shown in Figure D-3.

In each log line, cut-to-length logs are scanned by the turner laser scanners, and the turner optimizer calculates the optimal breakdown solution and the associated angle by which the log needs to be rotated by the log turner. Because the checks and other attributes are not measured, optimization is based solely on the shape of logs provided by the laser scanners.

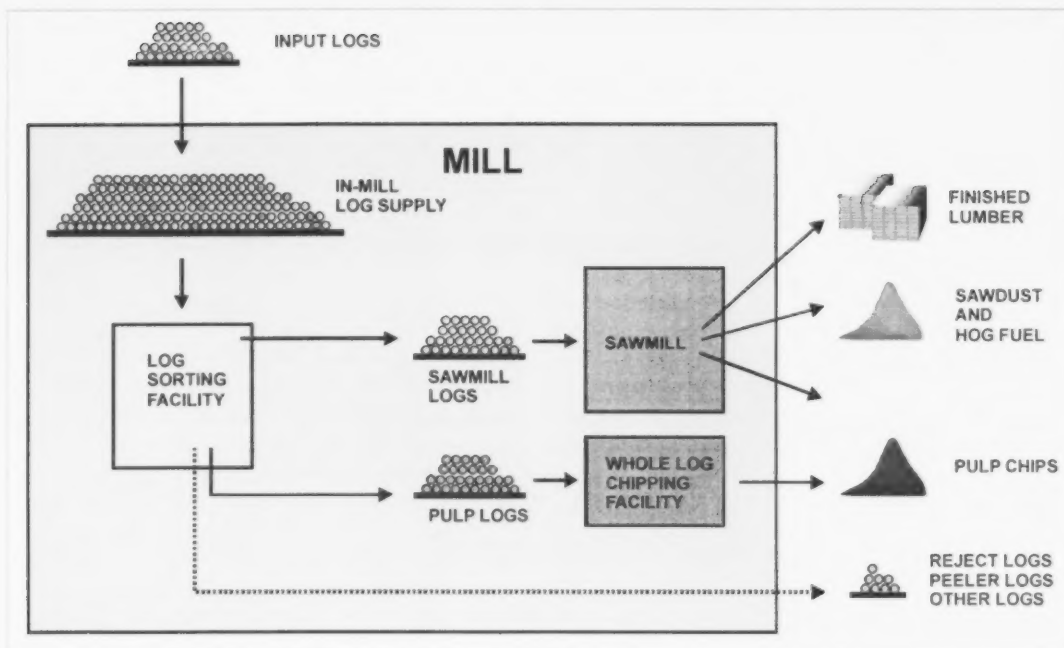


Figure D-2. Operation of the log sorting sawmill.

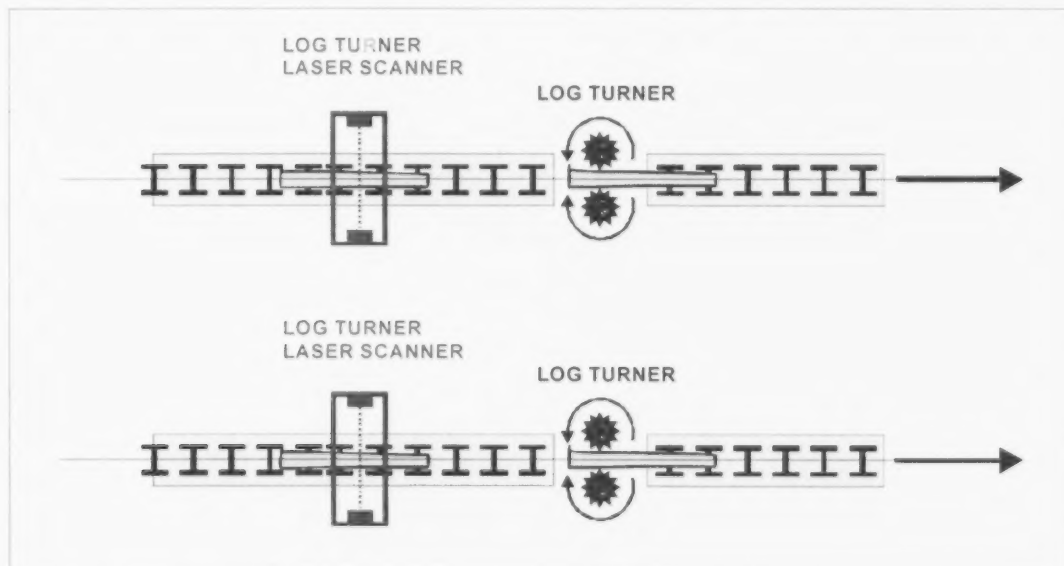


Figure D-3. Front end of a Current Mill with two log lines.

Alternative A

In this alternative, an X-ray scanner is integrated into both log lines (Figure D-4).

In each log line, the logs are scanned by both the turner laser scanners and the X-ray scanners. The log sorting/optimizing software decides what to do with the log on the basis of the log shape provided by the laser scanners, and based on the checks and other log attributes derived from the X-ray scans. The sorting/processing decision is based on the log attributes and/or the optimal breakdown solution and the associated estimated value recovery. The sawmill logs have the appropriate log attributes (such as

acceptable spirality of grain) and above-minimum value recovery. The reject, non-sawmill logs have either higher value (such as peeler logs), or lower value (such as pulp mill or biomass logs) than sawmill logs. These reject logs need to be transferred from the log turner conveyors and the sawmill to the log yard and transported to other destinations. The sawmill logs would be processed in the usual manner, but of course with higher recovery than in the Current Mill.

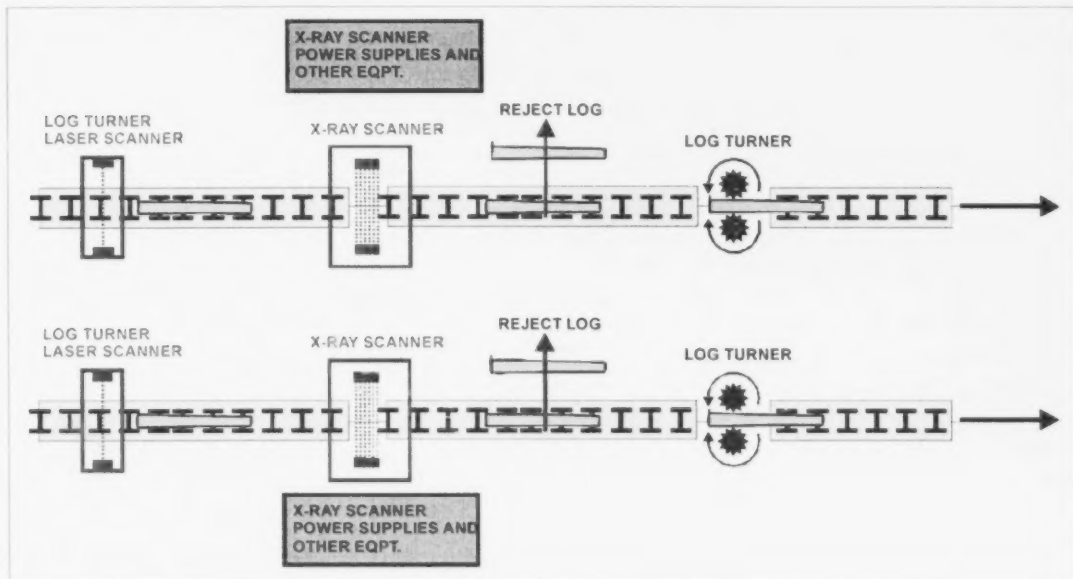


Figure D-4. Alternative A: X-ray scanner is integrated into both log lines.

Alternative B

In this alternative, one laser system and one X-ray scanning system service two log lines (Figure D-5).

This design has the same capability as Alternative A (Figure D-4), but it requires a transfer mechanism to move logs from the “scanning” line to the other log line. The transfer should be such that the orientation of logs would remain unchanged to ensure that the subsequent optimal log rotation in the log turner can be achieved. Such precise transfer of logs could be difficult to achieve.

Alternative C

If the log transfer in Alternative B cannot be done accurately, consideration could be given to spraying reference lines on each log at any convenient location before the transfer. This would require adding a line for spraying equipment and incurring the spraying costs but these costs would be more than offset by the increased lumber recovery that would result from more accurate log rotation. This is defined as Alternative C (Figure D-6).

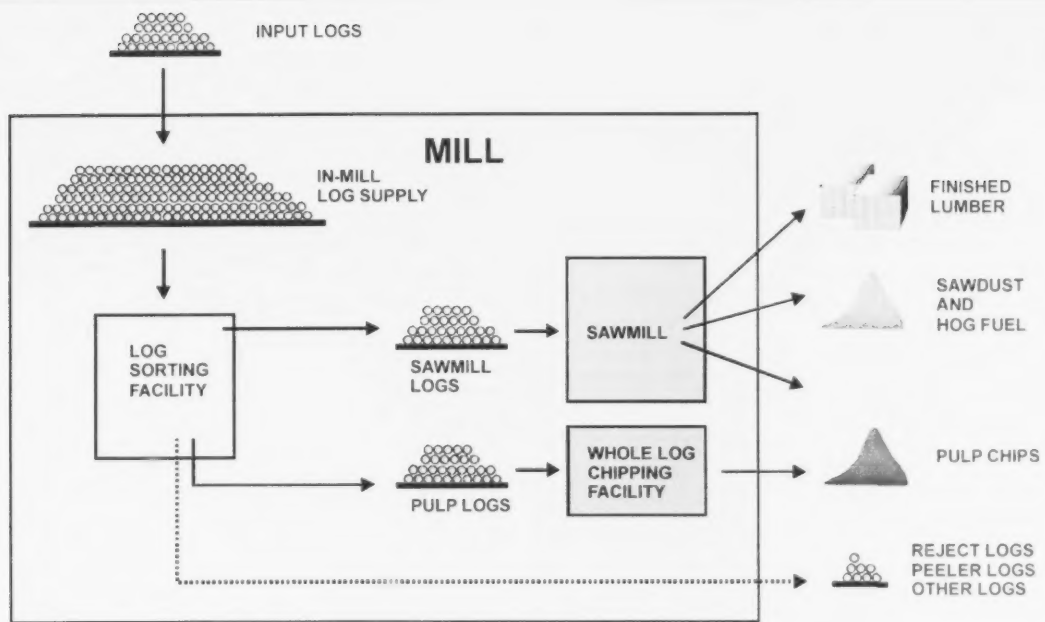


Figure D-2. Operation of the log sorting sawmill.

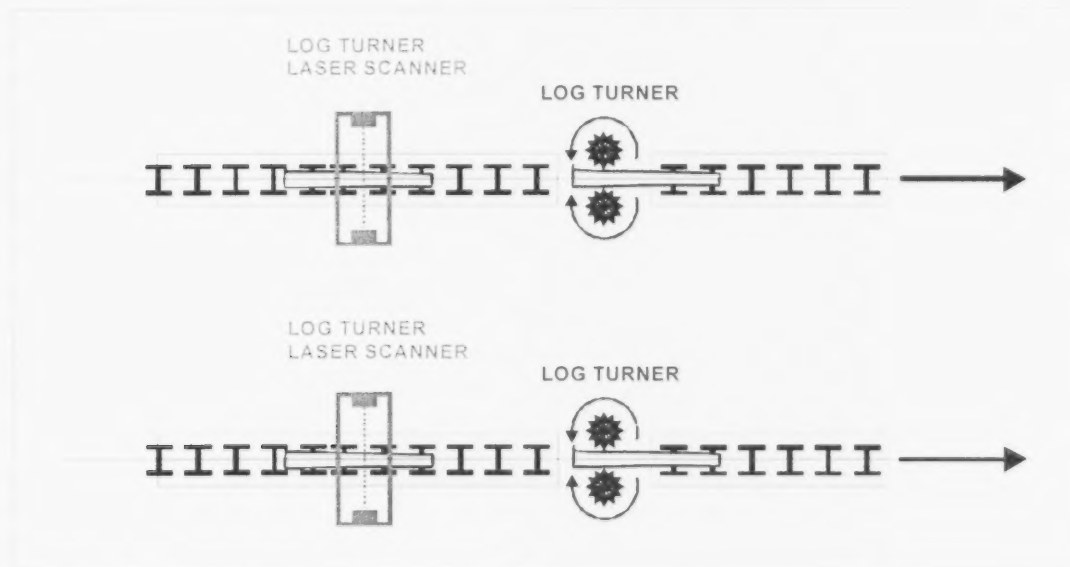


Figure D-3. Front end of a Current Mill with two log lines.

Alternative A

In this alternative, an X-ray scanner is integrated into both log lines (Figure D-4).

In each log line, the logs are scanned by both the turner laser scanners and the X-ray scanners. The log sorting/optimizing software decides what to do with the log on the basis of the log shape provided by the laser scanners, and based on the checks and other log attributes derived from the X-ray scans. The sorting/processing decision is based on the log attributes and/or the optimal breakdown solution and the associated estimated value recovery. The sawmill logs have the appropriate log attributes (such as

acceptable spirality of grain) and above-minimum value recovery. The reject, non-sawmill logs have either higher value (such as peeler logs), or lower value (such as pulp mill or biomass logs) than sawmill logs. These reject logs need to be transferred from the log turner conveyors and the sawmill to the log yard and transported to other destinations. The sawmill logs would be processed in the usual manner, but of course with higher recovery than in the Current Mill.

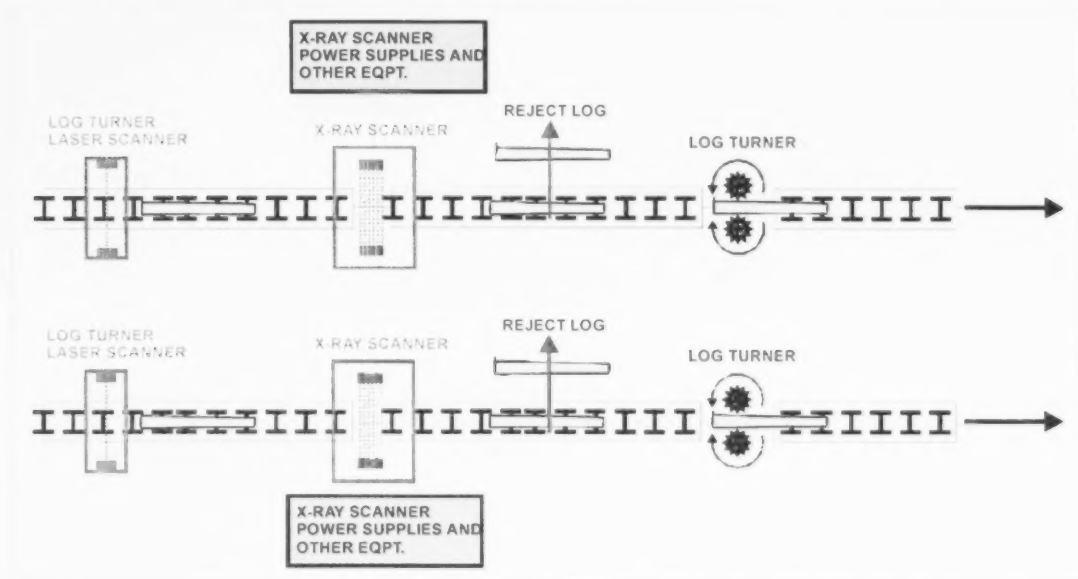


Figure D-4. Alternative A: X-ray scanner is integrated into both log lines.

Alternative B

In this alternative, one laser system and one X-ray scanning system service two log lines (Figure D-5).

This design has the same capability as Alternative A (Figure D-4), but it requires a transfer mechanism to move logs from the "scanning" line to the other log line. The transfer should be such that the orientation of logs would remain unchanged to ensure that the subsequent optimal log rotation in the log turner can be achieved. Such precise transfer of logs could be difficult to achieve.

Alternative C

If the log transfer in Alternative B cannot be done accurately, consideration could be given to spraying reference lines on each log at any convenient location before the transfer. This would require adding a line for spraying equipment and incurring the spraying costs but these costs would be more than offset by the increased lumber recovery that would result from more accurate log rotation. This is defined as Alternative C (Figure D-6).

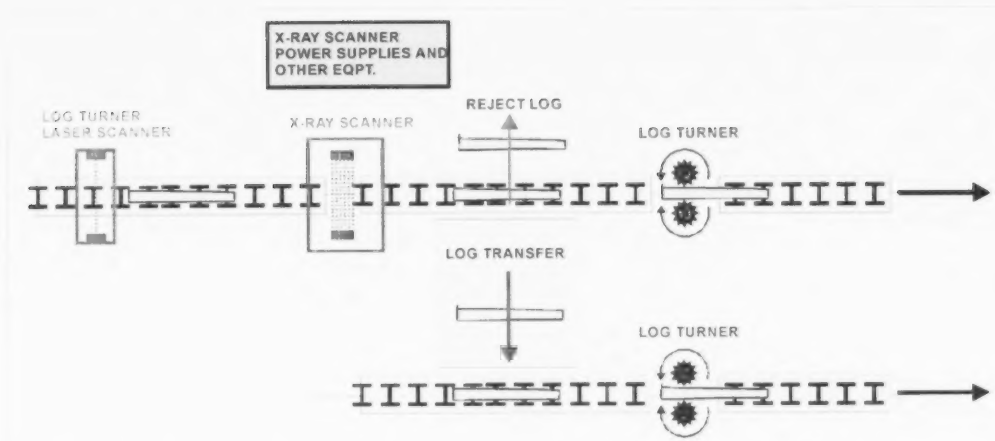


Figure D-5. Alternative B: one laser and one X-ray scanning system service two log lines.

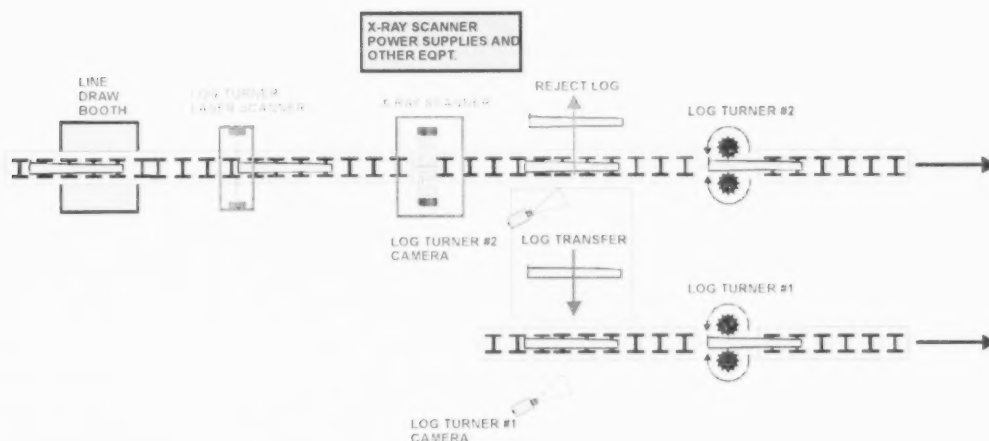


Figure D-6. Alternative C: front end of a sawmill.

Pros and Cons of the Alternatives

Each alternative has advantages and disadvantages:

- Alternative A has the highest capital cost because it requires two laser systems and two X-ray scanning systems, but it does not require a transfer deck. Although the time required to optimize the log would be twice as long as for Alternatives B or C, the processing decisions would be more accurate.
- Alternatives B and C have lower capital cost, but a transfer deck is required. The time to optimize the log would be half the time required in Alternative A.
- Alternative C probably has the best return on investment of the three designs.

Comparison of Log Yard and In-sawmill Sorting Alternatives

Comparing the log yard and in-sawmill log sorting/optimization alternatives is to some extent akin to comparing apples and oranges.

Identifying the better alternative requires considering the following aspects:

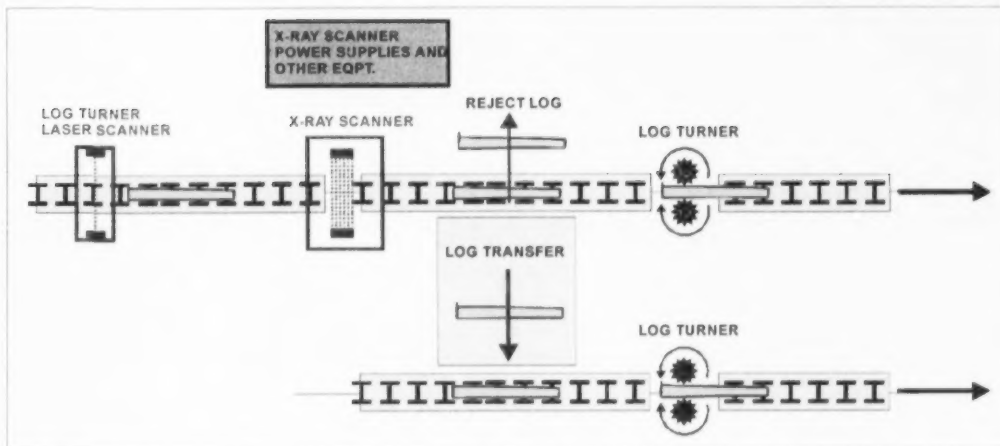


Figure D-5. Alternative B: one laser and one X-ray scanning system service two log lines.

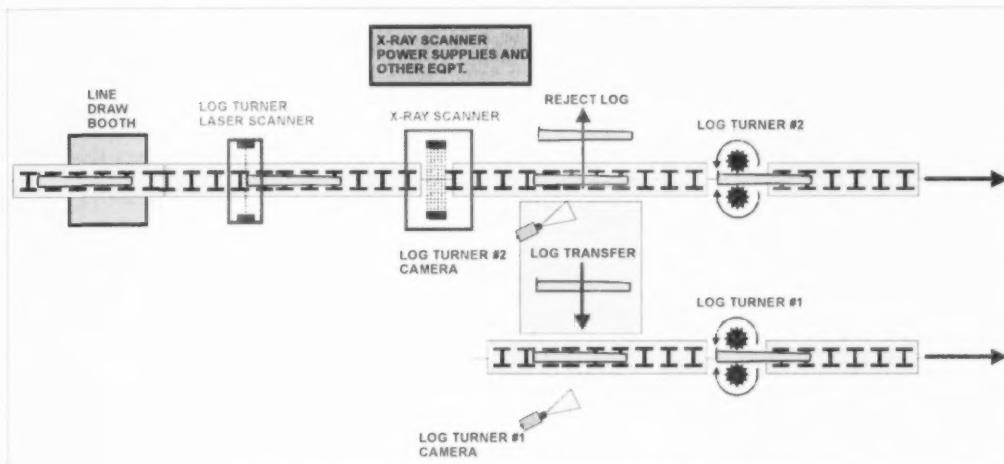


Figure D-6. Alternative C: front end of a sawmill.

Pros and Cons of the Alternatives

Each alternative has advantages and disadvantages:

- Alternative A has the highest capital cost because it requires two laser systems and two X-ray scanning systems, but it does not require a transfer deck. Although the time required to optimize the log would be twice as long as for Alternatives B or C, the processing decisions would be more accurate.
- Alternatives B and C have lower capital cost, but a transfer deck is required. The time to optimize the log would be half the time required in Alternative A.
- Alternative C probably has the best return on investment of the three designs.

Comparison of Log Yard and In-sawmill Sorting Alternatives

Comparing the log yard and in-sawmill log sorting/optimization alternatives is to some extent akin to comparing apples and oranges.

Identifying the better alternative requires considering the following aspects:

Operational Limitations

Log yard sorting facility

- No limit on log length.
- Barked logs.
- May operate completely independently of sawmill operation, i.e., it could operate 3 shifts/day, 7 days/week, and its operation would not be interrupted by stoppages of other machine centers in the sawmill.
- Requires two to four staff to operate the facility, deliver logs to the log deck, and remove logs from the log bins.

In-sawmill sorting facility

- Operates only when the sawmill operates and hence its operation would be interrupted by stoppages of other machine centers in the sawmill.
- Probably requires one or two staff to operate the log transfer deck and remove logs from the reject log bins.

Installation Limitations

Log yard sorting facility

- Can be built in a log yard without affecting existing sawmill operations.
- Requires constructing buildings to house the laser and X-ray scanners, log loading deck with operator's building, and in-feed and out-feed conveyors; and new utilities have to be provided.

In-sawmill sorting facility

- Requires substantial re-building of the front end of existing sawmill, which could interfere with the sawmill operation.
- Does not require construction of buildings to house the laser and X-ray scanners, log loading deck with operator's building, and in-feed and out-feed conveyors; and only some new utilities would have to be provided.

Information Retention and Lumber Recovery

Log yard sorting facility

- Unless a breakthrough in technology occurs, the information about log attributes (including checks) and optimal breakdown solution would be retained only partially—perhaps by using line drawings on the log ends.
- Value recovery from sawmill logs would depend on the information retention, but it would most likely be lower than for the in-sawmill sorting alternative.

In-sawmill sorting facility

- Value recovery from sawmill logs would be high because the information about log attributes (including checks) and the optimal breakdown solution would be retained and fully utilized in the log breakdown.

Appendix E. Sawing patterns associated with different levels of X-ray scanning capability

This appendix summarizes how, in various scenarios, OPTITEK® would assign sawing patterns to simulated logs based on:

- how well the simulated sawmill could detect the positions of checks and use this information to optimize manufacturing and
- the level of checking included in the log models.

The levels of checking are:

- No checks.
- Checks detectable by imperfect X-ray scanner (i.e., X-ray Mill Not Perfect scenario).
- All checks, including checks that only a perfect X-ray scanner could detect (i.e., X-ray Mill Perfect scenario).

Figure E-1 shows the sawing patterns and relative values that OPTITEK® would assign to the various combinations of check-detection ability and level of checking. Each scenario uses the same hypothetical log. This relationship between the value recoveries of the different scenarios is studied to estimate the value recovery that could be achieved with the X-ray scanner in the X-ray Mill Perfect scenario or X-ray Mill Not Perfect scenario.

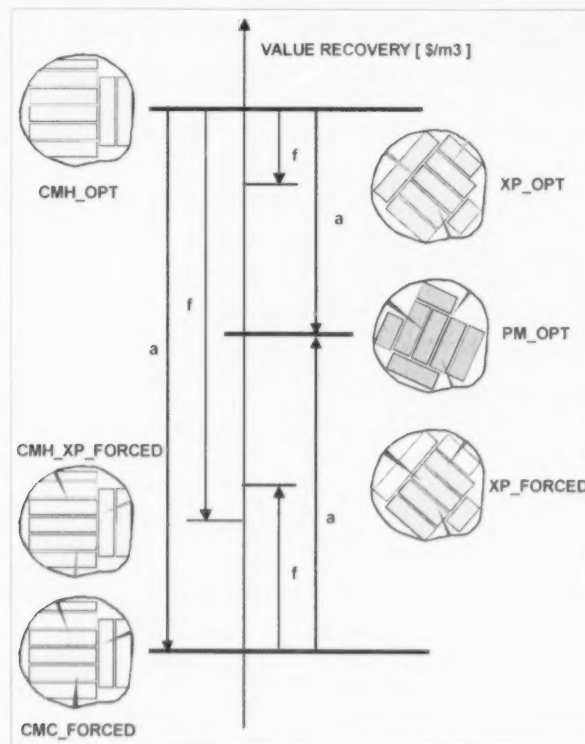


Figure E-1. Relationship between value recoveries of selected scenarios.

CMH_OPT is an optimal pattern, based on the log shape only, that corresponds to a healthy, check-free log, and thus provides the highest possible value recovery. This pattern would be used by the Current Mill processing logs not affected by the mountain pine beetle.

CMC_FORCED is the same as CMH_OPT. It includes all checks “overlying” the pattern, which lowers the grade of some boards or loses them altogether. This sawing pattern usually has the lowest value recovery. This pattern would be used by the Current Mill processing beetle-affected logs.

PM_OPT is an optimal pattern based on all machine centres having perfect knowledge of log shape and all checks.

XP_OPT is an optimal pattern based on the log shape and only the checks detected by the X-ray scanner. This pattern would be used in processing beetle-affected logs in a sawmill equipped with an X-ray scanner and all machine centers using only the detected checks in optimizing breakdown .

XP_FORCED is the same pattern as XP_OPT, but the valuation includes the non-visible checks “overlying” the pattern, which further lowers the grade of some boards or some boards are even lost altogether. The value recovery of this sawing pattern is lower than PM_OPT and usually higher than CMC_FORCED. The value recovery of XP_FORCED is what would be actually realized in a Current Mill processing beetle-affected logs, and where the mill is equipped with an X-ray scanner and XP_OPT is the optimal pattern (based on only the “visible” checks) used in all machine centers for optimizing breakdown .

CMH_XP_FORCED is the same as the CMH_OPT, but the log models include checks detected by the X-ray scanner “overlying” the pattern, which lowers the grade of some boards or some boards are even lost altogether. Because detected checks are a subset of all checks, the value recovery of this sawing pattern is less than CMH_OPT and usually more than CMC_FORCED. The value recovery of CMH_XP_FORCED is what would be actually realized in a Current Mill processing beetle-affected logs, and where the mill is equipped with an X-ray scanner for sorting/valuation purposes, but where XP_OPT is not “attached” to the log; hence the normal CMH_OPT is used in all machine centers for optimizing breakdown.

Factor “f” is the ratio of value recoveries of a log with and without checks associated with a particular scenario (Figure E-1). Based on Figure E-1 and the factor “f”, the following observations (Table E1) can be made about the consequences of the X-ray scanner limitations in detecting checks:

Table E1. Effect of *f* on relative Pattern Values.

$f=1$ (all checks are detected perfectly)	$XP\_OPT = XP\_FORCED = PM\_OPT$ $CMH\_XP\_FORCED = CMC\_FORCED$
$0 < f < 1$ (only some checks are detected)	$XP\_OPT > PM\_OPT > XP\_FORCED$ $CMH\_OPT > CMH\_XP\_FORCED > CMC\_FORCED$
$f=0$ (no checks are detected)	$XP\_OPT = CMH\_OPT$ $XP\_FORCED = CMC\_FORCED = CMH\_XP\_FORCED$

The above relationships can be roughly approximated by using the factor *f* as:

$$XP\_FORCED = CMC\_FORCED + f \times (PM\_OPT - CMC\_FORCED)$$

$$XP\_OPT = CMH\_OPT + f \times (PM\_OPT - CMH\_OPT)$$

$$CMH\_XP\_FORCED = CMH\_OPT + f \times (CMC\_FORCED - CMH\_OPT)$$

As already mentioned, the value recoveries for $f = 0.50$, and others for reference, were calculated and tabulated for the scenarios of interest in this project.

Appendix F. Lumber products and prices

Tables F-1 and F-2 summarize pertinent product file inputs that describe the lumber mix to be produced. Table F-3 shows prices of byproducts that resulted from the simulation.

Table F-1. Lumber sizes and lengths, nominal and rough green target.

	Lumber sizes		Lumber lengths	
	Nominal (inches)	Rough green target (inches)	Nominal (ft)	Rough green target (inches)
Thickness	2	1.654	8	98.00
	4	3.73	10	122.50
			12	147.00
Width	6	5.77	14	171.50
			16	196.00

Table F-2. Lumber grades used in sawing simulation.

OPTITEK Grade	Industry grade	Maximum wane			Maximum shake				Max. split
		Thickness (%)	Width (%)	Length (%)	Length	Width	Through	Edge	
1	J-grade	23.2	7.3	10.0	24"	1/32"	Not permitted	Not permitted	Not permitted
2	MSR	25.5	28.8	100	24"	No limit	Not permitted	Not permitted	W
					36" or ¼ L	No limit	Not permitted	Yes	1.5 L
3	No. 2 & Btr	34.5	28.3	100					
					24"	No limit	Yes	Not Permitted	W
4	No. 3	41.8	45.9	100	1/3 L	No limit	Yes	Yes	1/6 L
		72.5	59.8	25.0					
5	Economy	57.2	62.1	100	80%	No limit	Yes	Yes	1/3 L
		59.9	86.0	25.0					

Notes: W=width; L=length;

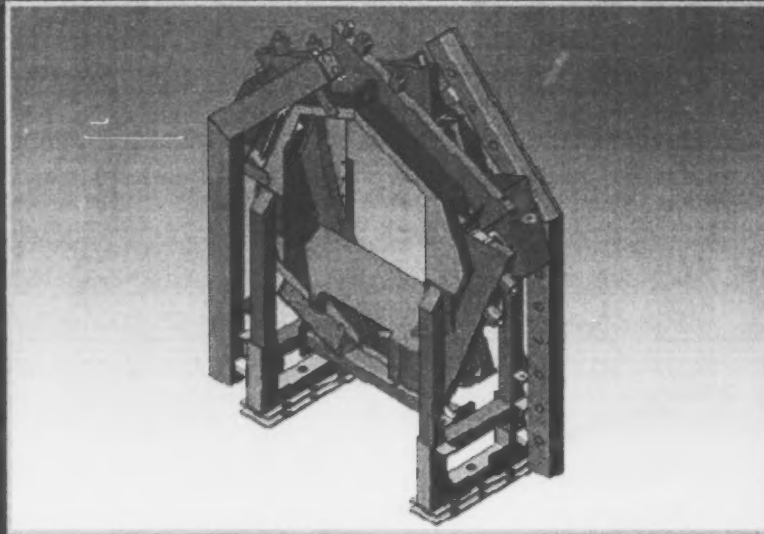
Table F-3. Byproduct prices.^a

Byproduct	\$/bone dry unit	\$/metric tonne	\$/m ³ of solid wood
Chips	76.27	70.00	28.63
Sawdust	8.72	8.00	3.27

Appendix G. Bintec X-ray scanner

Wood-X 1D-4D

*X-ray Computer Tomography System
for Grading Logs and Timber*



Benefits

- Grading Accuracy
- Reliability
- New Process Management
- Higher Yield
- Pine, Spruce, Birch
- Interfaces to:
 - 3D Scanners
 - Mill Net
- Order based log grading

Essential Features

- Knots: volume and quality
- Knotless surface
- Ring width
- Diameter of the heartwood
- Foreign objects
- Rot
- Density
- Strenght grading parameters
- Identification: Log by log ID and Butt, Middle or Top Log

BINTEC OY, FINLAND • www.bintec.fi

Figure G-1. Schematic of the Bintec X-ray scanner, and summary of features.

Bintec Oy is a Finnish company that manufactures X-ray log scanners for the European forest products industry. Table G-1 summarizes the information provided by Bintec's X-ray scanner. Bintec Oy has also developed rudimentary software algorithms for check detection and image processing, but the software has not been fully developed because of lack of demand/need for check detection in the company's usual market of northern Europe.

A Bintec X-ray log scanner is installed at UPM's Kaukas sawmill in Finland where it is used for sorting logs in the log yard. MPM Engineering Ltd., a Canadian company specializing in sawmill optimization and system integration, has been working with Bintec at the Kaukas sawmill and has developed a solid working relationship with both companies.

At the Kaukas sawmill, the Bintec X-ray log scanner operates at line speeds of up to 600 ft/min and provides four-view digital radiographs at a resolution of approximately 1 mm across the log width and 3 mm along the length. The system has been used for sorting pine logs in five sawmills in Europe.

Both the geometric, true-shape, laser scanning system and the Bintec X-ray system are located within a building that provides the required climate control and protection from the elements (Figure G-1).

After passing through the geometric and Bintec X-ray scanning systems, the logs are conveyed to the appropriate bins (62 in total) (Figure G-2).

Table G-1. Capabilities of Bintec Oy's system for X-ray scanning of logs: summary .

Features	Accuracy	Reliability (%)
Butt, middle or top log	Based on specified features	>95
Diameter		
On bark	±1 to 2 mm	>95
Under bark	±1 to 2 mm	>95
Knot clusters		
Number	±0	>95
Location	±3 to 5 mm	>95
Knotless surface quality	0 to 10, worst/best	>90
Knot volume	±5%	>90
In 90° sectors, min./max.	4 × 90°	>90
Quality of knot clusters	0 to 10, worst/best	>90
Ring width	±1–2 mm	>90
Diameter of the heartwood	±2 mm	>95
Foreign objects	Stones, metal, resin	>85
Rot (if different in density)	Volume/rate	>90
Length	±5 mm	>95
Skew	±2 mm	>95
Volume	±2%	>95
Taper	±2 mm/m	>95
Density	±5%	>90
Strength grading parameters	f (knots, ring width, density)	>90
Checks	Under development	Under development

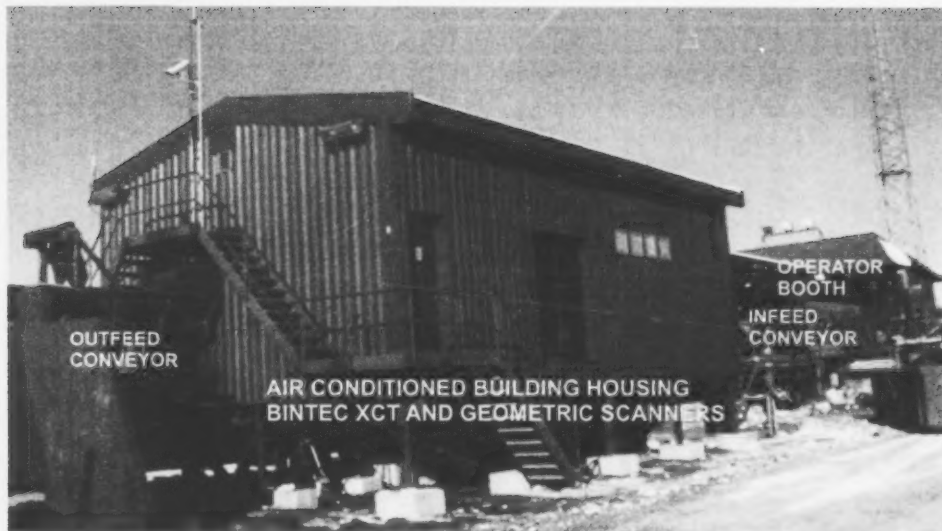


Figure G-1. Log sorting operations at one of UPM's sawmills.



Figure G-2. Bins for sorted logs.

Several other manufacturers also have one-, two-, and three-view commercial X-ray systems for use in sawmills, but their technologies appear to be less advanced than Bintec's.

Bintec and MPM formed a partnership to market complete systems using either or both X-ray and geometric scanning technologies for evaluating, sorting, and breaking down logs. The companies are prepared to further develop their respective technologies to facilitate processing beetle-affected logs. Bintec would provide hardware and software for the X-ray system. MPM would provide the geometric scanning system and the required software and be responsible for integration with Bintec's system.

MPM Engineering Ltd. and Bintec Oy collaborated on this project. MPM Engineering Ltd. represents Bintec Oy in Canada and may be contacted to provide information about Bintec Oy's X-ray log scanner. Specification details for a complete log sorting facility, including a Bintec X-ray scanner with six views, were provided in separate documentation (not included here) by Bintec Oy and MPM Engineering Ltd.

Appendix H: Lumber value recoveries from sample logs

Table H-1. Value of lumber recovery from sample logs, sorted as in scenarios, 2007 prices, simulated at 50%, Diameter Class 1.

		CMH_OPT healthy logs	CMC FORCED all checks	CMH_XP FORCED SIMULATED	PM_OPT all checks	XP_OPT visible checks	CMH_XNP FORCED visible checks	XP FORCED all checks	XNP_OPT visible checks	XNP FORCED all checks
log#	AvgDle (in)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)
1	7.8	98	87	92	98	98	87	92	98	85
2	7.8	98	87	92	93	95	87	90	93	63
3	7.7	110	95	102	97	104	29	96	112	29
4	6.6	109	91	100	99	104	96	95	110	77
5	6.6	109	91	100	95	102	110	93	110	91
6	7.9	97	79	88	81	89	62	80	80	67
7	7.8	98	79	88	98	98	87	88	98	98
8	7.2	111	87	99	97	104	66	92	107	49
9	7.2	111	87	99	101	106	82	94	107	78
10	7.2	111	87	99	97	104	82	92	107	75
11	7.7	110	85	98	94	102	29	90	105	29
12	7.7	110	82	96	102	106	29	92	105	29
13	5.9	97	72	85	91	94	66	82	94	89
14	6.9	98	72	85	85	91	79	78	89	63
15	6.4	104	76	90	90	97	49	83	87	61
16	7.2	111	80	96	101	106	66	91	107	85
17	5.4	110	77	94	95	103	66	86	111	77
18	5.4	110	77	94	95	103	66	86	111	77
19	6.9	103	72	87	99	101	86	85	96	64
20	6.9	98	66	82	89	93	66	78	74	74
21	7.8	98	65	81	98	98	83	81	98	64
22	6.3	98	65	82	69	84	47	67	86	53
23	7.4	104	68	86	92	98	52	80	92	53
24	6.9	98	64	81	73	86	64	69	73	73
25	6.7	109	68	88	79	94	56	73	83	40
26	6.7	112	70	91	82	97	70	76	70	59
27	7.1	104	65	84	65	84	48	65	72	47
28	7.0	93	56	75	63	78	34	60	64	47
29	6.9	98	58	78	84	91	66	71	89	55
30	6.6	109	64	87	99	104	91	81	110	69
31	6.4	104	59	81	90	97	49	74	85	82
32	5.4	110	62	86	95	103	84	79	99	77
33	5.4	110	62	86	104	107	84	83	99	48
34	6.9	103	56	80	86	95	74	71	104	37
35	7.9	97	52	75	73	85	45	63	57	57
36	7.4	104	56	80	87	96	59	72	91	79
37	6.7	112	60	86	81	97	70	70	72	56
38	6.7	112	60	86	90	101	70	75	90	76
39	6.7	112	60	86	90	101	80	75	96	79
40	7.7	110	57	84	93	101	29	75	112	29
41	6.6	109	56	83	90	100	91	73	102	72
42	6.3	98	49	74	75	87	47	62	86	69
43	6.3	98	49	74	69	83	47	59	86	69
44	6.3	98	49	74	69	84	47	59	86	53
45	7.4	104	52	78	89	96	52	70	91	69
46	5.9	97	48	72	86	91	66	67	94	54
47	5.4	101	50	75	67	84	38	59	98	43
48	6.9	103	50	76	82	93	91	66	103	50
49	6.9	103	50	76	86	94	86	68	103	59
50	7.4	104	50	77	86	95	65	68	89	55
51	7.1	104	49	76	70	87	49	60	75	48
52	7.0	93	44	68	61	77	34	52	71	37
53	5.9	97	43	70	57	77	64	50	92	48
54	5.9	97	42	69	57	77	72	49	93	28
55	6.0	110	47	79	72	91	35	60	88	49
56	6.0	110	47	79	54	82	28	51	83	48
57	6.4	104	45	74	84	94	41	64	84	50
58	6.7	109	46	77	71	90	55	58	96	46
59	7.1	104	43	73	61	83	49	52	64	42
60	5.4	101	38	69	70	85	38	54	78	43
61	7.0	93	34	64	56	75	34	45	59	37
62	6.7	109	37	73	78	93	54	57	84	40
63	6.0	110	35	73	54	82	49	45	75	41
64	6.0	110	35	73	65	88	49	50	89	37
65	7.0	93	28	60	61	77	32	44	52	37
66	5.4	101	27	64	61	81	38	44	86	50
67	6.7	109	28	68	71	90	45	50	84	40

Appendix H: Lumber value recoveries from sample logs

Table H-1. Value of lumber recovery from sample logs, sorted as in scenarios, 2007 prices, simulated at 50%, Diameter Class 1.

		CMH_OPT healthy logs	CMC FORCED all checks	CMH_XP FORCED SIMULATED	PM_OPT all checks	XP_OPT visible checks	CMH_XNP FORCED visible checks	XP FORCED all checks	XNP_OPT visible checks	XNP FORCED all checks
log#	AvgDle (in)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)
1	7.8	98	87	92	98	98	87	92	98	85
2	7.8	98	87	92	93	95	87	90	93	63
3	7.7	110	95	102	97	104	29	96	112	29
4	6.6	109	91	100	99	104	96	95	110	77
5	6.6	109	91	100	95	102	110	93	110	91
6	7.9	97	79	88	81	89	62	80	80	67
7	7.8	98	79	88	98	98	87	88	98	98
8	7.2	111	87	99	97	104	66	92	107	49
9	7.2	111	87	99	101	106	82	94	107	78
10	7.2	111	87	99	97	104	82	92	107	75
11	7.7	110	85	98	94	102	29	90	105	29
12	7.7	110	82	96	102	106	29	92	105	29
13	5.9	97	72	85	91	94	66	82	94	89
14	6.9	98	72	85	85	91	79	78	89	63
15	6.4	104	76	90	90	97	49	83	87	61
16	7.2	111	80	96	101	106	66	91	107	85
17	5.4	110	77	94	95	103	66	86	111	77
18	5.4	110	77	94	95	103	66	86	111	77
19	6.9	103	72	87	99	101	86	85	96	64
20	6.9	98	66	82	89	93	66	78	74	74
21	7.8	98	65	81	98	98	83	81	98	64
22	6.3	98	65	82	69	84	47	67	86	53
23	7.4	104	68	86	92	98	52	80	92	53
24	6.9	98	64	81	73	86	64	69	73	73
25	6.7	109	68	88	79	94	56	73	83	40
26	6.7	112	70	91	82	97	70	76	70	59
27	7.1	104	65	84	65	84	48	65	72	47
28	7.0	93	56	75	63	78	34	60	64	47
29	6.9	98	58	78	84	91	66	71	89	55
30	6.6	109	64	87	99	104	91	81	110	69
31	6.4	104	59	81	90	97	49	74	85	82
32	5.4	110	62	86	95	103	84	79	99	77
33	5.4	110	62	86	104	107	84	83	99	48
34	6.9	103	56	80	86	95	74	71	104	37
35	7.9	97	52	75	73	85	45	63	57	57
36	7.4	104	56	80	87	96	59	72	91	79
37	6.7	112	60	86	81	97	70	70	72	56
38	6.7	112	60	86	90	101	70	75	90	76
39	6.7	112	60	86	90	101	80	75	96	79
40	7.7	110	57	84	93	101	29	75	112	29
41	6.6	109	56	83	90	100	91	73	102	72
42	6.3	98	49	74	75	87	47	62	86	69
43	6.3	98	49	74	69	83	47	59	86	69
44	6.3	98	49	74	69	84	47	59	86	53
45	7.4	104	52	78	89	96	52	70	91	69
46	5.9	97	48	72	86	91	66	67	94	54
47	5.4	101	50	75	67	84	38	59	98	43
48	6.9	103	50	76	82	93	91	66	103	50
49	6.9	103	50	76	86	94	86	68	103	59
50	7.4	104	50	77	86	95	65	68	89	55
51	7.1	104	49	76	70	87	49	60	75	48
52	7.0	93	44	68	61	77	34	52	71	37
53	5.9	97	43	70	57	77	64	50	92	48
54	5.9	97	42	69	57	77	72	49	93	28
55	6.0	110	47	79	72	91	35	60	88	49
56	6.0	110	47	79	54	82	28	51	83	48
57	6.4	104	45	74	84	94	41	64	84	50
58	6.7	109	46	77	71	90	55	58	96	46
59	7.1	104	43	73	61	83	49	52	64	42
60	5.4	101	38	69	70	85	38	54	78	43
61	7.0	93	34	64	56	75	34	45	59	37
62	6.7	109	37	73	78	93	54	57	84	40
63	6.0	110	35	73	54	82	49	45	75	41
64	6.0	110	35	73	65	88	49	50	89	37
65	7.0	93	28	60	61	77	32	44	52	37
66	5.4	101	27	64	61	81	38	44	86	50
67	6.7	109	28	68	71	90	45	50	84	40

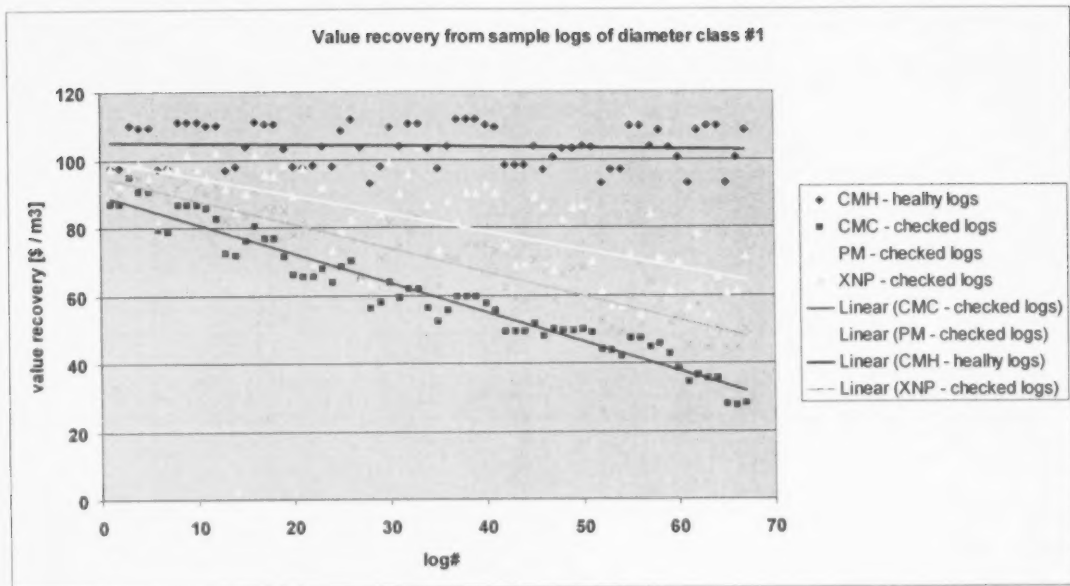


Figure H-1. Value recoveries from sample logs in Diameter Class 1.

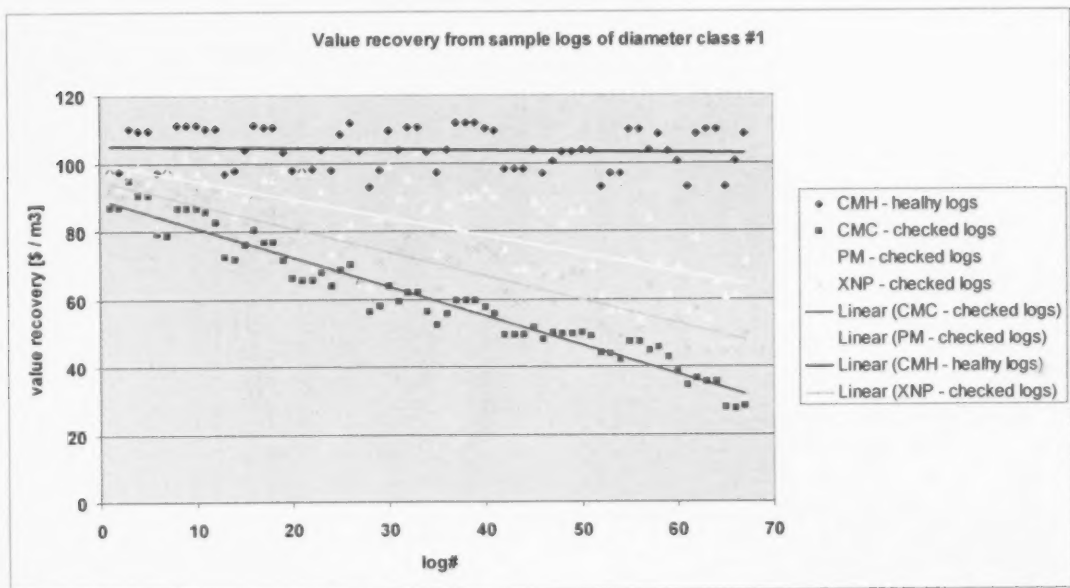


Figure H-2. Value recoveries from sample logs in Diameter Class 2.

Table H-2. Value recovery from sample logs, sorted as in scenarios, 2007 prices, simulated at 50%, Diameter Class 2.

log#	AvgDie	CMH_OP T healthy logs	CMC FORCED all checks	CMH_XP FORCED SIMULAT ED	PM_OPT all checks	XP_OPT visible checks	CMH_XN P FORCED visible checks	XP FORCED all checks	XNP_OPT visible checks	XNP FORCED all checks
	(in)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)
68	7.4	118	109	114	115	116	111	112	118	109
69	7.0	121	107	114	111	116	90	109	111	111
70	7.4	118	104	111	114	116	111	109	118	104
71	7.0	121	104	113	107	114	88	105	111	70
72	7.0	121	99	110	113	117	83	106	104	73
73	5.4	107	87	97	96	101	76	92	82	57
74	6.0	117	95	106	108	113	107	102	117	95
75	7.8	122	99	110	110	116	99	104	117	82
76	5.9	116	93	104	102	109	81	97	116	75
77	6.9	115	90	103	102	109	95	96	107	53
78	7.0	121	95	108	108	114	88	101	106	93
79	6.0	117	92	104	108	113	107	100	117	92
80	7.8	122	95	109	117	119	99	106	121	91
81	7.4	118	92	105	108	113	111	100	118	92
82	7.1	103	79	91	81	92	56	80	89	53
83	5.9	116	88	102	100	108	87	94	116	88
84	6.0	117	89	103	108	113	107	98	117	89
85	6.3	118	89	103	102	110	75	96	97	73
86	7.4	118	89	104	108	113	111	99	118	89
87	6.7	121	91	106	103	112	82	97	103	82
88	6.0	117	87	102	108	113	107	98	117	87
89	7.2	108	80	94	88	98	86	84	104	70
90	7.8	122	88	105	111	117	88	99	121	86
91	5.4	114	81	97	93	103	84	87	104	68
92	6.9	115	82	98	100	107	95	91	114	61
93	6.6	110	78	94	87	99	92	83	113	72
94	6.6	110	77	94	82	96	91	80	107	61
95	7.2	108	75	92	93	100	87	84	99	66
96	6.9	115	80	97	94	105	96	87	117	76
97	6.7	122	84	103	99	111	87	92	108	62
98	5.4	107	74	90	96	101	76	85	100	80
99	6.7	121	83	102	97	109	75	90	111	81
100	5.4	114	78	96	93	103	79	86	112	71
101	6.7	122	83	103	103	113	87	93	106	84
102	7.7	126	85	106	109	117	70	97	105	80
103	6.4	124	84	104	94	109	79	89	112	65
104	5.4	114	77	95	93	103	90	85	118	68
105	7.2	108	73	90	87	98	89	80	107	47
106	6.9	115	78	96	90	102	75	84	101	80
107	7.1	103	69	86	83	93	65	76	90	52
108	6.7	122	82	102	97	109	87	89	112	49
109	6.9	115	76	96	84	100	88	80	114	69
110	6.7	121	80	101	92	107	67	86	105	73
111	7.8	122	80	101	116	119	99	98	121	81
112	7.9	120	77	98	100	110	76	88	115	66
113	6.4	124	80	102	90	107	65	85	101	77
114	6.9	115	74	94	84	100	72	79	99	78
115	6.7	122	77	100	97	109	87	87	108	58
116	7.2	108	67	88	91	99	87	79	101	67
117	7.9	120	74	97	104	112	85	89	116	79
118	7.7	126	78	102	106	116	75	92	119	87
119	7.9	120	73	96	105	112	82	89	115	64
120	6.9	115	70	93	78	97	75	74	97	66
121	7.9	120	71	95	101	110	86	86	113	69
122	7.7	126	74	100	106	116	73	90	114	90
123	7.7	126	73	99	105	116	93	89	119	75
124	6.4	124	67	96	100	112	67	84	97	76
125	7.1	103	54	78	75	89	46	64	90	46
126	7.1	103	46	75	82	93	52	64	90	47

Table H-3. Value recovery from sample logs, sorted as in scenarios, 2007 prices, simulated at 50%, Diameter Class 3.

		CMH_OP T healthy logs	CMC FORCED all checks	CMH_XP FORCED SIMULAT ED	PM_OPT all checks	XP_OPT visible checks	CMH_XN P FORCED visible checks	XP FORCED all checks	XNP_OPT visible checks	XNP FORCED all checks
log#	AvgDle (in)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)
127	7.0	114	114	114	114	114	107	114	114	114
128	7.7	128	123	126	127	128	120	125	128	123
129	7.7	128	123	125	127	128	120	125	128	123
130	6.6	122	116	119	122	122	104	119	121	117
131	7.7	128	122	125	127	128	120	125	128	122
132	7.0	114	107	111	113	113	107	110	114	107
133	7.0	114	107	111	113	114	107	110	114	107
134	7.2	133	124	128	128	130	109	126	130	122
135	7.7	128	120	124	126	127	120	123	128	120
136	5.9	129	119	124	125	127	108	122	128	118
137	7.4	119	109	114	113	116	112	111	119	109
138	5.4	128	117	122	125	127	103	121	121	106
139	6.9	123	112	118	115	119	99	114	124	106
140	5.4	117	106	111	113	115	96	110	118	101
141	7.2	133	119	126	127	130	109	123	129	102
142	7.9	119	106	112	119	119	109	113	119	93
143	5.9	129	115	122	130	129	118	122	129	105
144	6.0	123	109	116	120	121	109	115	121	96
145	5.9	129	115	122	128	129	108	122	128	113
146	7.9	119	105	112	111	115	112	108	119	105
147	5.9	129	115	122	130	129	108	122	130	125
148	7.9	119	102	110	118	118	113	110	120	96
149	6.9	125	107	116	114	119	98	111	120	105
150	6.7	124	106	115	109	117	98	108	114	93
151	7.2	133	113	123	124	128	108	118	129	109
152	7.9	119	101	110	112	115	112	106	119	101
153	6.0	123	104	113	120	121	102	112	122	102
154	7.0	114	97	105	103	109	107	100	114	97
155	6.0	123	103	113	119	121	109	111	122	93
156	7.4	119	99	109	103	111	112	101	119	99
157	6.7	124	103	113	106	115	94	104	110	83
158	6.7	124	103	113	105	114	91	104	103	75
159	5.4	128	106	117	110	119	95	108	126	102
160	6.3	119	99	109	100	110	80	99	114	82
161	6.6	122	100	111	119	120	106	110	122	102
162	7.4	119	97	108	109	114	112	103	119	97
163	5.4	128	104	116	124	126	96	114	125	108
164	7.1	120	98	109	110	115	92	104	116	96
165	7.8	123	99	111	118	120	105	108	122	114
166	7.1	120	96	108	110	115	95	103	115	97
167	5.4	128	102	115	123	126	101	112	128	107
168	6.9	125	99	112	112	118	87	105	122	96
169	6.9	123	97	110	113	118	112	105	123	97
170	5.4	117	92	104	106	112	79	99	114	95
171	6.9	123	97	110	112	118	92	105	124	99
172	7.1	120	94	107	109	115	95	102	114	99
173	6.9	125	98	111	111	118	89	104	117	86
174	7.8	123	96	109	117	120	108	106	116	98
175	6.3	119	92	106	101	110	74	96	111	87
176	5.4	117	89	103	108	112	89	98	111	88
177	6.4	112	84	98	103	107	83	94	107	83
178	7.8	123	91	107	118	120	104	105	121	103
179	6.9	123	91	107	111	117	112	101	123	91
180	6.9	125	90	107	111	118	89	101	121	100
181	6.4	112	81	96	102	107	80	91	105	89
182	6.7	125	90	107	108	116	78	99	116	89
183	6.4	112	80	96	104	108	78	92	103	87
184	6.3	119	84	102	98	109	75	91	113	72
185	6.3	119	84	102	96	108	86	90	105	78
186	6.7	125	87	106	102	114	86	95	110	73
187	6.7	125	85	105	101	113	88	93	116	72
188	6.4	112	74	93	98	105	75	86	100	86

Table H-2. Value recovery from sample logs, sorted as in scenarios, 2007 prices, simulated at 50%, Diameter Class 2.

		CMH_OPT T healthy logs	CMC FORCED all checks	CMH_XP FORCED SIMULATED	PM_OPT all checks	XP_OPT visible checks	CMH_XN P FORCED visible checks	XP FORCED all checks	XNP_OPT visible checks	XNP FORCED all checks
log#	AvgDle (in)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)
68	7.4	118	109	114	115	116	111	112	118	109
69	7.0	121	107	114	111	116	90	109	111	111
70	7.4	118	104	111	114	116	111	109	118	104
71	7.0	121	104	113	107	114	88	105	111	70
72	7.0	121	99	110	113	117	83	106	104	73
73	5.4	107	87	97	96	101	76	92	82	57
74	6.0	117	95	106	108	113	107	102	117	95
75	7.8	122	99	110	110	116	99	104	117	82
76	5.9	116	93	104	102	109	81	97	116	75
77	6.9	115	90	103	102	109	95	96	107	53
78	7.0	121	95	108	108	114	88	101	106	93
79	6.0	117	92	104	108	113	107	100	117	92
80	7.8	122	95	109	117	119	99	106	121	91
81	7.4	118	92	105	108	113	111	100	118	92
82	7.1	103	79	91	81	92	56	80	89	53
83	5.9	116	88	102	100	108	87	94	116	88
84	6.0	117	89	103	108	113	107	98	117	89
85	6.3	118	89	103	102	110	75	96	97	73
86	7.4	118	89	104	108	113	111	99	118	89
87	6.7	121	91	106	103	112	82	97	103	82
88	6.0	117	87	102	108	113	107	98	117	87
89	7.2	108	80	94	88	98	86	84	104	70
90	7.8	122	88	105	111	117	88	99	121	86
91	5.4	114	81	97	93	103	84	87	104	68
92	6.9	115	82	98	100	107	95	91	114	61
93	6.6	110	78	94	87	99	92	83	113	72
94	6.6	110	77	94	82	96	91	80	107	61
95	7.2	108	75	92	93	100	87	84	99	66
96	6.9	115	80	97	94	105	96	87	117	76
97	6.7	122	84	103	99	111	87	92	108	62
98	5.4	107	74	90	96	101	76	85	100	80
99	6.7	121	83	102	97	109	75	90	111	81
100	5.4	114	78	96	93	103	79	86	112	71
101	6.7	122	83	103	103	113	87	93	106	84
102	7.7	126	85	106	109	117	70	97	105	80
103	6.4	124	84	104	94	109	79	89	112	65
104	5.4	114	77	95	93	103	90	85	118	68
105	7.2	108	73	90	87	98	89	80	107	47
106	6.9	115	78	96	90	102	75	84	101	80
107	7.1	103	69	86	83	93	65	76	90	52
108	6.7	122	82	102	97	109	87	89	112	49
109	6.9	115	76	96	84	100	88	80	114	69
110	6.7	121	80	101	92	107	67	86	105	73
111	7.8	122	80	101	116	119	99	98	121	81
112	7.9	120	77	98	100	110	76	88	115	66
113	6.4	124	80	102	90	107	65	85	101	77
114	6.9	115	74	94	84	100	72	79	99	78
115	6.7	122	77	100	97	109	87	87	108	58
116	7.2	108	67	88	91	99	87	79	101	67
117	7.9	120	74	97	104	112	85	89	116	79
118	7.7	126	78	102	106	116	75	92	119	87
119	7.9	120	73	96	105	112	82	89	115	64
120	6.9	115	70	93	78	97	75	74	97	66
121	7.9	120	71	95	101	110	86	86	113	69
122	7.7	126	74	100	106	116	73	90	114	90
123	7.7	126	73	99	105	116	93	89	119	75
124	6.4	124	67	96	100	112	67	84	97	76
125	7.1	103	54	78	75	89	46	64	90	46
126	7.1	103	46	75	82	93	52	64	90	47

Table H-3. Value recovery from sample logs, sorted as in scenarios, 2007 prices, simulated at 50%, Diameter Class 3.

		CMH_OP T healthy logs	CMC FORCED all checks	CMH_XP FORCED SIMULAT ED	PM_OPT all checks	XP_OPT visible checks	CMH_XN P FORCED visible checks	XP FORCED all checks	XNP_OPT visible checks	XNP FORCED all checks
log#	AvgDie (in)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)
127	7.0	114	114	114	114	114	107	114	114	114
128	7.7	128	123	126	127	128	120	125	128	123
129	7.7	128	123	125	127	128	120	125	128	123
130	6.6	122	116	119	122	122	104	119	121	117
131	7.7	128	122	125	127	128	120	125	128	122
132	7.0	114	107	111	113	113	107	110	114	107
133	7.0	114	107	111	113	114	107	110	114	107
134	7.2	133	124	128	128	130	109	126	130	122
135	7.7	128	120	124	126	127	120	123	128	120
136	5.9	129	119	124	125	127	108	122	128	118
137	7.4	119	109	114	113	116	112	111	119	109
138	5.4	128	117	122	125	127	103	121	121	106
139	6.9	123	112	118	115	119	99	114	124	106
140	5.4	117	106	111	113	115	96	110	118	101
141	7.2	133	119	126	127	130	109	123	129	102
142	7.9	119	106	112	119	119	109	113	119	93
143	5.9	129	115	122	130	129	118	122	129	105
144	6.0	123	109	116	120	121	109	115	121	96
145	5.9	129	115	122	128	129	108	122	128	113
146	7.9	119	105	112	111	115	112	108	119	105
147	5.9	129	115	122	130	129	108	122	130	125
148	7.9	119	102	110	118	118	113	110	120	96
149	6.9	125	107	116	114	119	98	111	120	105
150	6.7	124	106	115	109	117	98	108	114	93
151	7.2	133	113	123	124	128	108	118	129	109
152	7.9	119	101	110	112	115	112	106	119	101
153	6.0	123	104	113	120	121	102	112	122	102
154	7.0	114	97	105	103	109	107	100	114	97
155	6.0	123	103	113	119	121	109	111	122	93
156	7.4	119	99	109	103	111	112	101	119	99
157	6.7	124	103	113	106	115	94	104	110	83
158	6.7	124	103	113	105	114	91	104	103	75
159	5.4	128	106	117	110	119	95	108	126	102
160	6.3	119	99	109	100	110	80	99	114	82
161	6.6	122	100	111	119	120	106	110	122	102
162	7.4	119	97	108	109	114	112	103	119	97
163	5.4	128	104	116	124	126	96	114	125	108
164	7.1	120	98	109	110	115	92	104	116	96
165	7.8	123	99	111	118	120	105	108	122	114
166	7.1	120	96	108	110	115	95	103	115	97
167	5.4	128	102	115	123	126	101	112	128	107
168	6.9	125	99	112	112	118	87	105	122	96
169	6.9	123	97	110	113	118	112	105	123	97
170	5.4	117	92	104	106	112	79	99	114	95
171	6.9	123	97	110	112	118	92	105	124	99
172	7.1	120	94	107	109	115	95	102	114	99
173	6.9	125	98	111	111	118	89	104	117	86
174	7.8	123	96	109	117	120	108	106	116	98
175	6.3	119	92	106	101	110	74	96	111	87
176	5.4	117	89	103	108	112	89	98	111	88
177	6.4	112	84	98	103	107	83	94	107	83
178	7.8	123	91	107	118	120	104	105	121	103
179	6.9	123	91	107	111	117	112	101	123	91
180	6.9	125	90	107	111	118	89	101	121	100
181	6.4	112	81	96	102	107	80	91	105	89
182	6.7	125	90	107	108	116	78	99	116	89
183	6.4	112	80	96	104	108	78	92	103	87
184	6.3	119	84	102	98	109	75	91	113	72
185	6.3	119	84	102	96	108	86	90	105	78
186	6.7	125	87	106	102	114	86	95	110	73
187	6.7	125	85	105	101	113	88	93	116	72
188	6.4	112	74	93	98	105	75	86	100	86

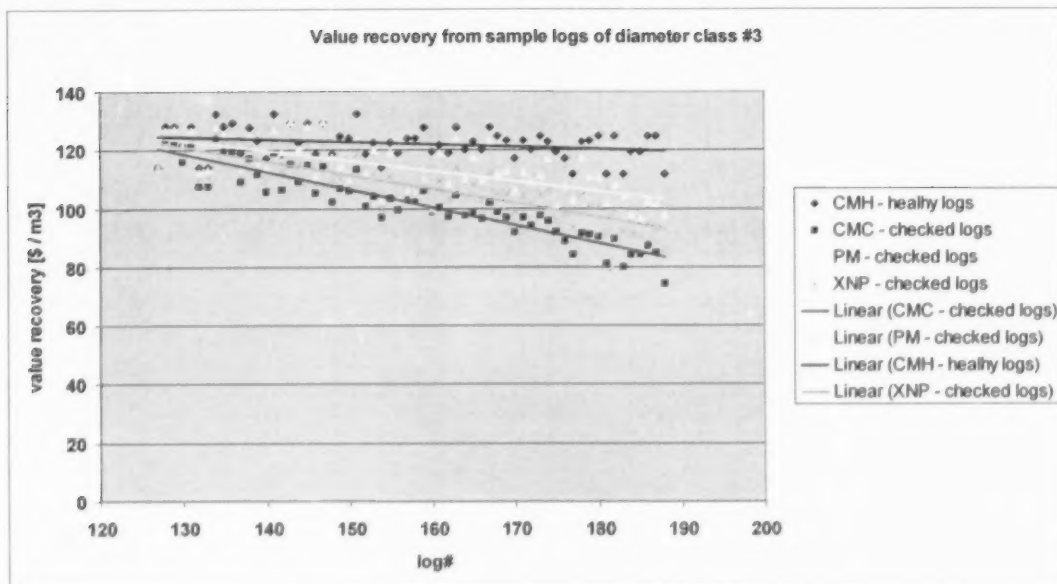


Figure H-3. Value recoveries from sample logs in Diameter Class 3.

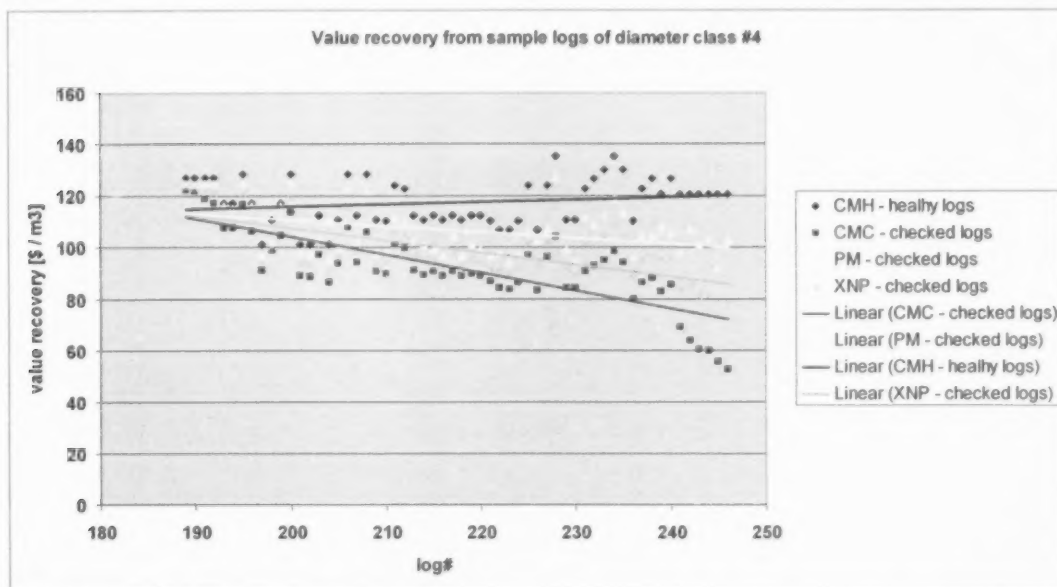


Figure H-4. Value recoveries from sample logs in Diameter Class 4.

Table H-4. Value recovery from sample logs, sorted as in scenarios, 2007 prices, simulated at 50%, Diameter Class 4.

		CMH_OP T healthy logs	CMC FORCED all checks	CMH_XP FORCED SIMULAT ED	PM_OPT all checks	XP_OPT visible checks	CMH_XN P FORCED visible checks	XP FORCED all checks	XNP_OPT visible checks	XNP FORCED all checks
log#	AvgDie (in)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)
189	7.8	127	122	125	125	126	107	123	127	122
190	7.8	127	122	124	124	126	111	123	128	120
191	7.8	127	119	123	125	126	111	122	127	125
192	7.8	127	117	122	125	126	111	121	128	115
193	6.7	117	108	112	116	117	98	112	117	116
194	6.7	117	108	112	115	116	92	111	117	108
195	6.4	128	117	123	125	127	100	121	128	111
196	6.7	117	106	112	116	117	95	111	117	107
197	6.9	101	91	96	97	99	85	94	101	87
198	6.0	110	99	105	102	106	100	100	110	88
199	6.7	117	105	111	116	117	96	110	117	105
200	6.4	128	114	121	125	127	95	119	127	102
201	6.9	101	89	95	98	100	81	94	98	89
202	6.9	101	89	95	98	99	81	93	102	92
203	7.7	112	97	105	103	108	81	100	106	78
204	6.9	101	86	94	95	98	81	91	99	82
205	6.0	110	94	102	99	105	98	96	110	93
206	6.4	128	108	118	123	126	105	116	128	115
207	6.9	112	94	103	102	107	85	98	105	95
208	6.4	128	106	117	122	125	86	114	125	114
209	5.9	110	91	101	98	104	78	94	97	93
210	7.9	110	90	100	98	104	85	94	103	93
211	5.4	124	101	113	112	118	98	106	119	94
212	7.0	123	100	111	109	116	93	104	122	91
213	7.7	112	91	102	102	107	82	97	107	91
214	6.0	110	89	100	101	106	96	95	111	89
215	6.9	112	91	101	99	106	81	95	104	85
216	5.9	110	89	100	97	104	72	93	100	85
217	7.7	112	91	101	105	109	88	98	109	84
218	5.9	110	89	100	97	103	76	93	99	92
219	6.9	112	90	101	101	107	79	95	107	92
220	7.7	112	89	101	99	106	86	94	108	90
221	7.9	110	87	98	97	103	81	92	103	85
222	7.1	107	84	95	98	102	68	91	99	85
223	7.1	107	84	95	94	100	74	89	98	94
224	7.9	110	86	98	98	104	82	92	102	86
225	5.4	124	97	110	106	115	99	102	120	94
226	7.1	107	83	95	102	104	70	93	99	89
227	5.4	124	96	110	107	116	97	102	120	95
228	5.4	135	104	120	127	131	0	116	133	107
229	6.0	110	84	97	99	105	96	92	110	87
230	5.9	110	84	97	95	103	78	90	103	79
231	7.0	123	91	107	112	117	98	101	124	85
232	6.7	126	93	110	109	118	93	101	116	83
233	6.3	130	95	113	113	121	109	104	126	92
234	5.4	135	98	117	119	127	0	109	129	98
235	6.3	130	94	112	113	122	100	104	124	88
236	7.9	110	80	95	96	103	85	88	103	78
237	7.0	123	86	105	105	114	94	96	124	90
238	6.7	126	88	107	105	116	92	96	115	85
239	7.2	121	83	102	108	114	88	95	118	72
240	6.7	126	86	106	106	116	84	96	113	89
241	7.2	121	69	95	98	110	82	84	113	72
242	6.6	121	64	92	107	114	80	85	113	73
243	7.2	121	60	91	101	111	75	81	114	73
244	7.2	121	60	90	103	112	85	82	117	83
245	6.6	121	55	88	92	106	76	74	112	66
246	6.6	121	53	87	103	112	83	78	111	67

Table H-4. Value recovery from sample logs, sorted as in scenarios, 2007 prices, simulated at 50%, Diameter Class 4.

		CMH_OPT T healthy logs	CMC FORCED all checks	CMH_XP FORCED SIMULAT ED	PM_OPT all checks	XP_OPT visible checks	CMH_XN P FORCED visible checks	XP FORCED all checks	XNP_OPT visible checks	XNP FORCED all checks
log#	AvgDle (in)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)	Val/Vnm (\$/m3)
189	7.8	127	122	125	125	126	107	123	127	122
190	7.8	127	122	124	124	126	111	123	128	120
191	7.8	127	119	123	125	126	111	122	127	125
192	7.8	127	117	122	125	126	111	121	128	115
193	6.7	117	108	112	116	117	98	112	117	116
194	6.7	117	108	112	115	116	92	111	117	108
195	6.4	128	117	123	125	127	100	121	128	111
196	6.7	117	106	112	116	117	95	111	117	107
197	6.9	101	91	96	97	99	85	94	101	87
198	6.0	110	99	105	102	106	100	100	110	88
199	6.7	117	105	111	116	117	96	110	117	105
200	6.4	128	114	121	125	127	95	119	127	102
201	6.9	101	89	95	98	100	81	94	98	89
202	6.9	101	89	95	98	99	81	93	102	92
203	7.7	112	97	105	103	108	81	100	106	78
204	6.9	101	86	94	95	98	81	91	99	82
205	6.0	110	94	102	99	105	98	96	110	93
206	6.4	128	108	118	123	126	105	116	128	115
207	6.9	112	94	103	102	107	85	98	105	95
208	6.4	128	106	117	122	125	86	114	125	114
209	5.9	110	91	101	98	104	78	94	97	93
210	7.9	110	90	100	98	104	85	94	103	93
211	5.4	124	101	113	112	118	98	106	119	94
212	7.0	123	100	111	109	116	93	104	122	91
213	7.7	112	91	102	102	107	82	97	107	91
214	6.0	110	89	100	101	106	96	95	111	89
215	6.9	112	91	101	99	106	81	95	104	85
216	5.9	110	89	100	97	104	72	93	100	85
217	7.7	112	91	101	105	109	88	98	109	84
218	5.9	110	89	100	97	103	76	93	99	92
219	6.9	112	90	101	101	107	79	95	107	92
220	7.7	112	89	101	99	106	86	94	108	90
221	7.9	110	87	98	97	103	81	92	103	85
222	7.1	107	84	95	98	102	68	91	99	85
223	7.1	107	84	95	94	100	74	89	98	94
224	7.9	110	86	98	98	104	82	92	102	86
225	5.4	124	97	110	106	115	99	102	120	94
226	7.1	107	83	95	102	104	70	93	99	89
227	5.4	124	96	110	107	116	97	102	120	95
228	5.4	135	104	120	127	131	0	116	133	107
229	6.0	110	84	97	99	105	96	92	110	87
230	5.9	110	84	97	95	103	78	90	103	79
231	7.0	123	91	107	112	117	98	101	124	85
232	6.7	126	93	110	109	118	93	101	116	83
233	6.3	130	95	113	113	121	109	104	126	92
234	5.4	135	98	117	119	127	0	109	129	98
235	6.3	130	94	112	113	122	100	104	124	88
236	7.9	110	80	95	96	103	85	88	103	78
237	7.0	123	86	105	105	114	94	96	124	90
238	6.7	126	88	107	105	116	92	96	115	85
239	7.2	121	83	102	108	114	88	95	118	72
240	6.7	126	86	106	106	116	84	96	113	89
241	7.2	121	69	95	98	110	82	84	113	72
242	6.6	121	64	92	107	114	80	85	113	73
243	7.2	121	60	91	101	111	75	81	114	73
244	7.2	121	60	90	103	112	85	82	117	83
245	6.6	121	55	88	92	106	76	74	112	66
246	6.6	121	53	87	103	112	83	78	111	67

